Sustainable urban drainage: Retrofitting for improved flood mitigation in city centres.

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Sustainable Urban Drainage – Retrofitting for Improved Flood Mitigation in City Centres

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Sustainable Urban Drainage – Retrofitting for Improved Flood Mitigation in City Centres

Report for Royal Institution of Chartered Surveyors

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Glossary and abbreviations

Sustainable Drainage Systems are a sequence of water management practices and facilities designed to drain surface water in a manner that will provide a more sustainable approach than the conventional practice of routing run-off through a pipe to a watercourse.

Water Sensitive Urban Design is an Australasian term encompassing SUDS principles, but extending to other water-related management practices (groundwater/wastewater management/water supply) with a focus on minimising environmental degradation and improving aesthetic/recreational aspects.

Central Business District is the preferred Australian and US term for the commercial area within an urban centre, comprising predominantly retail and office buildings. The UK term 'city centre' is less specific, as it implies a geographically central location (which may or may not reflect such commercial usage).

SPSS statistical analysis software

Greywater is waste water from wash hand basins, showers, baths, washing machines, dishwashers and kitchen sinks. This is distinct from 'blackwater', or sewage,

SUDS	Sustainable Urban Drainage Systems (original definition)
SuDS	Sustainable Drainage Systems (urban or rural) now more usually rendered 'SUDS'
WSUD	Water Sensitive Urban Design
CBD	Central Business District (city centres)
RICS	Royal Institution of Chartered Surveyors
SWMMs	Surface Water Management Measures
GIS	Geographic Information System
NLA	Net Lettable Area
EPSRC	Engineering and Physical Sciences Research Council

Executive Summary

Flood damage was estimated to cost A$20bn (£12.5bn) in Australia in 2011. In the UK approximately 185,000 commercial properties are at risk of flooding (Harman et al., 2002) and the 2007 flood event was estimated to cost businesses in England £0.75bn in damage and disruption (Chatterton et al., 2010). Surface water flash flooding of businesses has been driven by higher incidence of intense pluvial events; the lack of permeability in high density areas; and the inadequacy of drainage systems in city centres constructed to cope with different weather patterns and buildings. In the light of future uncertainties, it is becoming increasingly clear that the continuing reliance on piped drainage systems is creating unsustainable demands for ever-greater capacity, or the creation of underground storage facilities. As an alternative to expanding the existing 'grey' infrastructure systems, Sustainable Urban Drainage (SUDS) in the UK, and its equivalents elsewhere, are now being advocated and legislated for on a much wider scale.

Aim

The aim of this research was to examine the potential for mitigation of predominantly pluvial flooding in CBDs through retrofitting of such systems. The research used two case study areas to explore the challenges and opportunities for retrofit of SUDS in different cities with varying climate zones, urban design and governmental regimes. The research sought to:

a) Evaluate the potential to physically retrofit existing buildings and adjacent paved areas

b) Explore the potential for run of reduction and therefore mitigation of associated flood damage

c) Examine the costs and benefits of retrofitting SUDS and identify social and environmental benefits of sustainable drainage for commercial property and the business district.

In order to provide information and guidance for surveyors in the emerging area of retrofit of SUDS and provide material to build capacity of surveyors to contribute to improved drainage and flood mitigation for commercial property.

Methodology

The research commenced with a systematic literature review to identify the available information on the use and retrofit of SUDS to reduce flood risk. International databases of both academic and industry sources were accessed thereby creating a global picture of examples, together with available tools and guidance likely to be of benefit to the surveying community.

Using information drawn from the literature, criteria were developed to determine the technical requirements that determine suitability of roofs and paving areas for retrofit including the position, orientation and location of the building, the roof pitch, weight limitations and ground conditions.

Two detailed building databases were then developed for Melbourne, Australia and Newcastle, UK. The databases were compiled drawing on a wide range of sources, including existing commercial and publicly available databases, Google maps and visual inspections. The final building databases contained 526 commercial buildings in Melbourne and 507 commercial buildings in Newcastle.

The technical criteria were used to identify those buildings which had the potential to be retrofitted and to estimate the potential for retrofit of permeable paving. A simple estimation method was applied to the data derived from the property databases and available land use data to assess the potential run-off reduction under three scenarios. For the Melbourne dataset a further run-off analysis was carried out on the behalf of the research by the University of Newcastle using a state of the art rainfall inundation model.

Results and implications

The most appropriate and well understood SUDS for retrofit in city centre locations are green roofs, permeable paving and rain gardens. Combination of these features into a 'management train' or 'treatment train' (a linked series of drainage techniques) can increase the attenuation potential of individual features.

The evidence base for estimating the direct benefits of SUDS retrofit is rapidly developing. Both academic studies and city-wide assessments have been undertaken. For green roofs, benefits accrue to individual property owners in terms of reduced energy bills owing to the insulating properties of such roofs.

The broader stakeholder community also derives benefits from green SUDS installation such as roofs and rain gardens, some of which are less easily monetised. They include: biodiversity/wildlife habitat; improvements in water and air quality; and attenuation of the urban heat island effect. Green roofs also have a carbon sequestration function.

The range of benefits of permeable paving are more limited and relate to stormwater management and water quality. However permeable paving may have a lifecycle cost advantage over other paving systems thereby representing a no regret option for renewal of urban paving.

The consideration of the full range of benefits and their applicability from the perspective of actors engaged in the installation of measures is a recent development in the literature and has not yet been explored for commercial property owners and investors.

The database analysis of buildings within two city centres revealed that the proportion with potential for retrofit of green roofs is fairly low (under conservative assumptions). Estimation of other surfaces potentially suitable for permeable retrofit in busy business districts also reveals that a large proportion of urban hard surface may be unsuitable for standard permeable paving systems.

Estimation of the run off reduction potential for these two cases study areas can be seen to be realistically around 10-20%, however this can still make a significant contribution to stormwater reduction and peak attenuation. For both of the case study sites however it was seen to be necessary to consider the wider catchment area due to the presence of historic watercourses and topographical features.

Recommendations

Output from this research includes a summary of existing best practice guidance for chartered surveyors to use across all RICS regions. There has, however, been a great deal of work around this topic that has been done during the 18 months since this project was first conceived: for example, in the UK, guidance documents are being produced at the present time by the Construction Industry Research and Information Association, for example (CIRIA, 2013).

Guidance notes and checklists specifically for scoping potential integrated retrofit projects for commercial property surveyors are recommended and could be developed in the light of recent and ongoing research over the next twelve months.

The new conceptual model for owners and occupiers suggests that consideration of feedback from distributed benefits of green roof technology and permeable paving through property value and reputational gains could be highly influential. Further research is recommended in the measurement and attribution of costs and benefits of green roofs, specifically in the valuation of multiple benefits and the operationalisation of the conceptual model.

Further research is also needed on the performance of sustainable drainage systems under a variety of locational, climate and antecedent conditions both in terms of storm-water management and other benefits.

Detailed retrofit audits of the wider catchment for Melbourne and Newcastle are recommended.

1.0 Introduction

The motivation behind this research is to enhance the knowledge regarding minimisation of flood damage and disruption within the commercial property sector using retrofit of sustainable drainage. Much flood research in the past has focussed on the residential sector with some damage estimation and business continuity advice for individual businesses in central business districts (CBDs). However, business districts have unique characteristics and are comprised of a variety of property types linked by common, publically accessible, spaces that may be seen as essential to the functioning of the businesses choosing to locate in the district. Equally the viability of a business district has impacts on all those that work there, patronise the businesses and own or invest in the property. Therefore the consideration of flood mitigation within business districts must be considered at a variety of spatial scales and from the perspective of multiple stakeholders.

1.1 Flooding in Central Business Districts

Weather patterns are changing in ways consistent with a warming global climate (Solomon and Qin, 2007; Met Office Hadley Centre for Climate Research, 2007). Although specific extreme events cannot be attributed to climate change, the consensus is that the frequency of intense rainfall events is rising over most land masses (including those where average rainfall is decreasing) and this is likely to continue in some seasons (Solomon and Qin, 2007). Such intense rainfall events can cause flash floods, particularly in dense urban areas with low permeability, leading to serious impacts on the affected owners and occupiers.

In Australia, the more usual prolonged droughts have been replaced by increased rainfall: the estimated cost of building remediation following the 2010/11 floods in the states of Queensland and Victoria vary from A$9 billion to A$20 billion (Companies and Markets, 2011). The densely populated East Coast area has also been subject to severe floods in two consecutive years, including an event in which 29 mm of rain fell in a period of 30 minutes at Perth Airport (Bureau of Meteorology, 2012), whilst the Bureau of Meteorology issued Severe Weather Warnings for heavy rain and flash flooding over much of northern and eastern Queensland in March 2012.

In the UK, the cost of flash flooding has also risen in recent decades; 3.8 million properties in England are estimated to be at risk from surface water flooding alone (Environment Agency, 2013). Extreme rainfall events in 2007 and 2012 caused localised flash flooding in city centres including Glasgow, Hull, Newcastle and York, with substantial damage and disruption to the central business districts.

The real cost to the local economies may be long lasting and difficult to measure, as many businesses fail to recover after suffering flooding (Cumbria Intelligence Observatory, 2010; Ingirige and Wedawatta, 2011; Wedawatta et al., 2011).

1.2 Rationale

The growing damage impacts of increased pluvial flooding are not attributable to changing weather patterns alone: this is exacerbated by increased development pressures and urbanisation (Jha et al., 2011). In the UK, for example, there have been effects arising from the policy of redeveloping brown-field sites, together with the popularity of paving green spaces to provide car parking; likewise, in Australia, urban planning has increased the density of development and amount of impermeable surfaces. Stormwater runs swiftly off these surfaces, rather than slowly infiltrating into the ground, as it would have done on open or agricultural land. Furthermore, in many business districts, piped drainage systems were installed at a time when lower density development existed and their design has not been updated to accommodate the increased runoff (French et al., 2011). Retrofitting such below-ground drainage systems (both greywater and combined systems) is not only expensive, but time consuming and consequently highly disruptive to the businesses affected.

An alternative approach is to make use of measures designed to restore, or mimic, natural infiltration patterns; by decreasing runoff volumes and attenuating peak flows, the risk of urban flooding is reduced. Within business districts, this approach could involve the wide spread retrofit of green roofs, permeable paving and other surface or near-surface drainage options (Charlesworth and Warwick, 2011). Infiltration and storage devices, such as permeable paving, can be employed around commercial premises to reduce runoff, whilst green roofs and rainwater gardens can absorb rainwater, thereby attenuating peak flows. Urban renewal or refurbishment provides an opportunity for such retrofitting initiatives: in the US this approach has been adopted in both New York (NYC Environmental Protection, 2011; NYC Environmental Protection, 2012) and Portland, Oregon. In the latter case, in order to increase the uptake of green roofs and disconnection of downspouts, financial incentives were offered (Environmental Services – City of Portland, 2006; Environmental Services – City of Portland, 2011). Doubts have, however, been raised as to whether widespread retrofit is a viable option structurally or functionally (Wilkinson and Reed, 2009); furthermore, the contribution to cost effective reduction of flood risk from property level adaptation is yet to be fully explored (Lamond and Proverbs, 2009; Joseph et al., 2012).

1.3 Aims and objectives

The aim of this research was to examine the potential for mitigation of pluvial flooding in CBDs through retrofitting of sustainable urban drainage systems (SUDS). The study focuses on the commercial office sector in Melbourne, Australia and Newcastle, UK. Through extensive literature and document review, and through constructing and analysing a detailed property database, the research incorporated the following objectives:

1. To evaluate the potential proportion of buildings which could be physically retrofitted with green roof technology, and the potential for adjoining CBD spaces to be retrofitted with permeable paving;
2. To explores the potential reduction in rainwater run-off from green roof retrofit in Newcastle and Melbourne;
3. To analyse the costs and benefits of SUDS retrofit for flood risk reduction, identifies additional social and environmental benefits of green roof retrofit and develops a conceptual model for green roof retrofit to commercial buildings;
4. To identify and summarise available guidance for retrofitting SUDS on commercial buildings for the benefit of surveyors.

This study was, therefore, designed to critically synthesise existing evidence from diverse strands of literature and identify future research needs in the area of retrofitting sustainable drainage in central business districts.

2.0 Methods and Data

The research adopted a case study approach to explore the challenges and opportunities of retrofitting SUDS in two cities in different hemispheres. This was appropriate in order to broaden the consideration of climate, built environment, cultural and governmental factors that can influence the potential to retrofit SUDS in CBDs. The cities were selected based on a variety of factors including pragmatic considerations such as ease of access to data. However, as discussed below they were also identified as having similarities in flood characteristics that are useful for comparative purposes and an identified need to consider alternative drainage systems. Typical problematic features of business districts with surface water issues were identified in these cities and the lessons drawn from studying these case studies can therefore inform the factors considered when embarking on detailed evaluations of retrofit potential for other cities across the globe.

2.1 Literature review

A systematic literature review protocol was designed to identify the available information on the use of sustainable drainage systems in urban areas to reduce flood risk (and associated flood damages) either by reducing runoff volumes or attenuating peak flows. The terminology used varies considerably, not only between different countries, but also over time: for example, in the UK the acronym 'SUDS', although originally specific to urban drainage, has now come to mean sustainable drainage in any setting. The term 'Green infrastructure' is used in a number of countries; another UK term is 'Surface water management measures' (SWMMs); in the USA relevant terminology includes 'Stormwater control measures (SCMs), 'Best management practices' (BMPs) and 'Low Impact Development' (LIDs); in Australasia 'Water Sensitive Urban Design' (WSUDs) is the favoured descriptor. (In the interests of simplicity, the term SUDS, which is most commonly used in the UK, will be used throughout this report). Similarly, green roofs can also be termed 'living roofs', 'vegetated roofs' or 'ecoroofs', and the adjectives 'permeable' and 'pervious' are both used in connection with paving methods. Multiple definitions were, therefore, included in the review in order to ensure relevant material from all English language sources were captured. Standardised parameters, encompassing a wide range of subject terms, intervention types and outcome descriptors, were specified within the project protocol; these were used to search databases of both academic and industry sources. The results were then filtered to identify those elements most appropriate for retrofitting application in CBDs, thereby creating an international picture of examples, together with available tools and considerations likely to be of benefit to the surveying community.

2.2 Database design and population

The research method comprised the compilation of two detailed building databases; one for Melbourne, Australia and one for Newcastle in the UK. The databases contained information related to the existing building stock in the city centre or CBD for Melbourne. The databases were compiled using multiple sources such as existing commercial databases. For example Cityscope in Australia contains information about buildings such as year of construction, form of construction, building size, owners and tenants. Other building data was collated from the Property Council of Australia (PCA). Publicly available databases such as PRISM, which is assembled by the Victorian Government, and the Heritage database were also used to compile detailed building data. In the UK information was taken from the Valuation Office Agency, CoStar database and Ordnance Survey's Mastermap. Building data was sourced by researchers in the UK and Australia from Google Earth and Google Streetview. Finally, the researchers made visual inspections and photographed city centre / CBD buildings. Following a comprehensive validation phase the final building database contains 526 commercial buildings in the Melbourne CBD and 507 commercial buildings in three postcode sectors in Newcastle city centre.

2.3 Analysis of retrofit potential

Based on a comprehensive literature review with regards to green roof design and retrofit issues, a number of factors were identified to be taken into account when deciding if a roof was suitable for a green roof retrofit. Given the parameters for the design of green roofs noted in the literature the factors were evaluated on the basis of whether the existing roof could meet the design requirements of those factors for which data was available. This exploratory study aimed to determine the extent of the potential for green roof adaptations within the Melbourne CBD and Newcastle city centre and therefore details on the structural strength of the buildings was not collated due to time constraints and considering the significant number of buildings in the analysis. Given the research team's professional Chartered Building Surveying background and expertise a visual inspection was deemed sufficient at this stage to evaluate the general likely load bearing capacity of the buildings.

A research objective was to determine whether a green roof on a particular building was;

a) a viable option,

b) not a viable option or

c) possibly a viable option.

Using the Google Map search engine it was possible to view the roof from close quarters; this permitted determination of whether the roof was steeply pitched or otherwise, whether there was plant and services equipment on the roof which might have a detrimental effect on planting, or if the building was overshadowed partially i.e. completely or not at all. The compilation of these detailed databases of building characteristics enabled the evaluation of the potential for green roof retrofit to existing CBD buildings. The Australian database was compiled and verified using Microsoft Excel with the analysis undertaken in SPSS version 17, whereas the Newcastle database was compiled in SPSS version 19.

2.4 Methods for calculating run off reduction and damage estimation

Suitable methods and tools for calculating run off reduction and flood damage reduction were determined from the literature. In the examination of potential methods consideration was given to the purpose and spatial scale of calculation methods and tools. The review focussed on methods suitable for evaluation of run-off from green roof and permeable paving installation and metrics available to convert run-off estimates to flood damage reduction. Much of the existing literature on these matters derives from the United States but greatest weight was given to literature from the UK and Australia.

A simple estimation method was applied to the data derived from the property databases and raw GIS data from Melbourne and Newcastle in order to assess the potential run-off reduction under three scenarios:

- All roof, pavement and road surfaces retrofit
- Suitable roof, pavement and road surfaces retrofit
- Half of suitable roof, pavement and road surfaces retrofit

For the Melbourne dataset a further run-off analysis was carried out on the behalf of the research team by the University of Newcastle, using a state of the art inundation model that has been developed by Glenis et al. (2013) This further analysis was undertaken in order to more precisely estimate the impact of green roof retrofit on suitable rooftops in the Melbourne CBD. Three model runs were undertaken:

- Business as usual, no retrofit
- All rooftops retrofit
- Suitable rooftops retrofit

The differences in run off patterns were then examined spatially.

2.5 Development of a conceptual model for the CBD

The evidence base for estimating the direct benefits of green roofs is a rapidly developing field. Both academic studies and city-wide assessments of retrofitting plans have been undertaken, evaluating some of benefits and relating them to installation costs. Benefits accrue to individual property owners in terms of reduced energy bills owing to the insulating properties of such roofs (Bamfield, 2005; Bastien et al., 2011). For example, over the expected 40 year life of a green roof, it has been estimated that the benefit to an individual property owner was $43,500 (in respect of heating in winter and cooling in summer) (Bureau of Environmental Services – City of Portland, 2008). The broader stakeholder community also derives benefits from green roofs, but these aspects are less easily monetised. They include: biodiversity/wildlife habitat (Livingroofs.org, 2005; Vila et al., 2012); improvements in air quality (Stovin et al., 2012); and attenuation of the urban heat island effect (Vila et al., 2012; Stovin et al., 2012). Green roofs also have a carbon sequestration function, with an average of 375 g C m^2 being reported (Getter and Rowe, 2009); this aspect offers a potentially valuable contribution to reducing global greenhouse gas emissions. Although some detailed guidance aimed at working out the various direct costs and benefits of green roofs in commercial building does exist (for example, Groundwork Sheffield, 2011) this is limited to the developers' viewpoint. The consideration of the full range of benefits and their applicability from the perspective of actors engaged in the installation of measures is a recent development in the literature (Abbott et al., 2013) and has not yet been explored for commercial property owners and investors.

Another aspect typically omitted from the Water Sensitive Urban Design (WSUD) literature is the potential for indirect benefits accruing to commercial property owners and investors: these arise as a consequence of benefitting the wider community, both in terms of flood risk mitigation and the creation of more sustainable commercial buildings. Whilst the greening of business districts may also imply the creation of improved amenity and neighbourhood effects, the evidence for such impacts is sparse and contradictory (CABE Space, 2006; Sinnett et al., 2011). Empirical evidence from the real estate literature for the economic value of 'greening' buildings to owners and occupiers is also somewhat mixed (Sayce et al., 2010) but there are theoretical models of the impact of sustainability claims for commercial buildings which are predicated on lower utility costs, reputational effects, the form of commercial leases, the demand for green property, health and wellbeing of the buildings occupants, and the views of the investment market (Rapson et al., 2007). Therefore, an innovative conceptual model was required as a necessary first step in advising commercial owners and occupiers in the development of the business case for retrofit of green roof technology.

Image source: Silken Photography / Shutterstock.com

3.0 Results

The first two subsections of the results present the findings from the literature review and database analysis as they emerged from the two phases of research. The final two subsections draw together these results to present:

1. an overview of the physical retrofit potential to mitigate flood damage via reduction of run-off in the two study areas under three scenarios;
2. a new conceptual model that provides a framework for evaluating the distributed costs and benefits of green roof retrofit within central business districts from the perspective of the commercial property owner or occupier.

These two sections are designed to reflect the interests of, respectively, surveyors and planners within city authorities considering the potential to pursue retrofit programmes; and surveyors advising commercial property clients on the potential to benefit from installing green roofs on their particular property.

3.1 Literature Review

3.1.1 Types of SUDS suitable for retrofit in CBD

SUDS techniques can be designed to restore groundwater infiltration routes, or to provide storage methods that can mitigate the impacts on either watercourses or traditional storm water conveyance systems (Jumadar et al., 2008). In the context of retrofitting drainage solutions in high density urban areas, the availability and cost of allocating land to such features can pose a major barrier to adoption. This has lead to a preference for dual purpose installations, such as green roofs and permeable paving options. By controlling stormwater runoff at its source, such devices can (at least in part) mimic a location's pre-development flow regime, in terms of reduced runoff volumes and attenuated peak flows (Damodaram et al., 2010). When used in conjunction with piped drainage systems, the resulting augmentation of total capacity can delay, or obviate the need for, costly and disruptive upgrades to the existing drainage infrastructure.

The evidence demonstrates that SUDS techniques most appropriate for retrofitting purposes are as follows:

Figure 1 **Amy Joslin memorial Eco-Roof, Multnomah county headquarters building, Portland**

Case study – Green roof

16,000 square feet of retrofit green roof in the centre of Portland provides an amenity space with adjacent benches and is open to the public. Monitoring over an eighteen month period showed a peak flow reduction of 86% and 25% run off reduction for the building shortly after installation, with performance expected to increase over time. Other benefits of the roof include a 5-10% reduction in air conditioning load (Kurtz, 2010).

Green Roofs/vegetated roofs/ecoroofs

According to Voyde et al. (2010) green roofs are highly suitable stormwater controls for retrofitting in dense urban areas. As roofing can account for up to 50% of the impermeable surfaces in an urban area, a major opportunity to decrease runoff is thus presented (Stovin, 2010). Water can be stored both within the growing medium and in the plants themselves; it is then released via evapo-transpiration after a time-delay, dependent upon conditions such as the antecedent moisture content (Stovin, 2010). This can relieve pressure on other stormwater devices, though in more extreme storm events capacity will be exceeded and the design must take this into account (Balmforth et al., 2006).

Green roofs can safely be retrofitted only where the strength of the building structure permits the increased loading (for example, as discussed in Nophadrain, 2012); the substitution of suitable lightweight materials in the substrate may reduce the 'dead load' involved, however, with examples being 'crumb rubber' from recycled tyres, (Ristvey et al., 2010; Vila et al., 2012) and specially treated waste expanded polystyrene foam (Compton, 2006). Other considerations for suitability include avoidance of overshadowing likely to inhibit vegetation growth and the degree of pitch of the roof (Wilkinson and Reed, 2009), together with the choice of plant species, with those suited to maritime climates (MacIvor and Lundholm, 2011) differing from those required in, say, a sub-tropical zone. The installation of green roofs on existing buildings is, self-evidently, reliant upon the support of the owners and occupiers of relevant properties, unlike municipally-led drainage programmes. Incentive schemes to aid the uptake of green roofing have successfully been employed in both New York City (Bloomberg and Strickland, 2012b) and Portland (Environmental Services – City of Portland, 2011).

Figure 2 **Permeable paving in the Dings, Bristol, UK.**

Case study – Permeable paving

SUDS were included as part of a Home Zone scheme designed to improve the neighbourhood and increase the use of sustainable transport options such as walking and cycling. Permeable paving was fitted to 3 streets in which there are 120 houses. Local drainage systems were operating at capacity and the local water company would not allow any further connections to the drainage system to relieve the local ponding problems but the infiltration capacity of the soil allowed for installation of permeable surfaces. The Home Zone scheme was therefore seen to have multiple benefits in terms of surface water management and liveability. Residents were involved in the design of the scheme and 82% approved it (Centre for Transport and Society – UWE, 2005; Digman et al., 2012).

Permeable surfacing methods

There are three main types: porous pavements (such as porous asphalt and pervious concrete) that infiltrate water across the entire surface; permeable pavers (such as block pavers or plastic grids) in which water drains through the spaces or joints between impermeable elements; and reinforced soil, in which a system of modular cells (of concrete or plastic) is added to increase the load-bearing capacity and prevent compaction of the turf, grass or gravel surface material (Barr Engineering Company, 2011). In contrast with green roofs, permeable pavements can perform extremely well in severe rainfall conditions: in one study, it was demonstrated that the average infiltration rate achieved was 162 mm/h after an hour of wetting, far in excess of the 50 mm/h rainfall intensity typically used for highway drainage design (Stevens and Ogunyoye, 2012b).

It has been estimated that it is possible to retrofit at least half of the off-road impermeable surfaces in the UK with such equivalents and, as traditional surfaces such as bitumen and concrete require periodic resurfacing, there is a naturally occurring opportunity to replace these with more sustainable alternatives at the end of their useful life (Gordon-Walker et al., 2007). Permeable surfaces typically have a lower overall lifecycle cost, as their reduced maintenance costs outweigh initial capital costs: although extra excavations are required to lay them, future replacement of worn out paving blocks is not as expensive as the extensive digging required to renew worn out tarmac or concrete surfaces (Gordon-Walker et al., 2007).

Figure 3 Example of a Rain Stormwater planter in central Portland, USA.

Case study – Rain gardens

A program of stormwater management in Portland includes widespread use of vegetated infiltration devices such as stormwater planters and raingardens. Regular testing and monitoring is carried out to ensure the continued capacity of the devices to reduce run off. However the amenity benefits of the devices have also been assessed. Low capacity of the water treatment plants in Portland was a driving influence behind the green infrastructure programme and the installations are expected to contribute to energy (and, therefore, greenhouse gas reductions) due to their role in stormwater management. Another expected benefit of the raingardens is increases in residential property prices of 3.4-5% (ENTRIX, 2010).

Rain gardens/stormwater planters

Other installations suitable for retrofitting in some circumstances can include 'rain gardens' (or porous landscape detention areas) and stormwater planters. Where reduction in runoff volume alone is required, these can be constructed to allow water to seep into the surrounding soils (Cahill et al., 2011). A variation on this method incorporates a process to treat the pollutants found in stormwater runoff, in which case the term 'bioretention' may be used to describe them. This approach may be useful where, for example, groundwater might be at risk from pollutants in the runoff (Barr Engineering Company, 2011). Rain gardens can be incorporated into an existing site, for example by disconnecting downspouts from piped drainage systems (Environmental Services – City of Portland, undated) but, in order to achieve the water quality benefits, additional (potentially disruptive) engineering works may be required to install underground tanks in which the treatment process occurs.

Figure 4 **Epler Hall stormwater planters are a combined stormwater management and rainwater harvesting system.**

Case study – Treatment train

The planters collect roof run off via concrete splash boxes and plaza run off via cobbles divert it first to some planters. Excess water is collected in a storage tank where a sand filter and ultraviolet treatment render it suitable for use for irrigation and public toilets in Epler Hall. Thus the system enhances the plaza aesthetically and saves the hall money on utility bills (Cahill et al., 2011).

Image source: authors own

Combined SUDS methods/treatment trains

It should be noted that SUDS elements are often used in combination in order to yield the maximum benefit over a given catchment area. For dense urban environments, the two methods discussed above could, therefore, form components of an optimal strategy for flood mitigation.

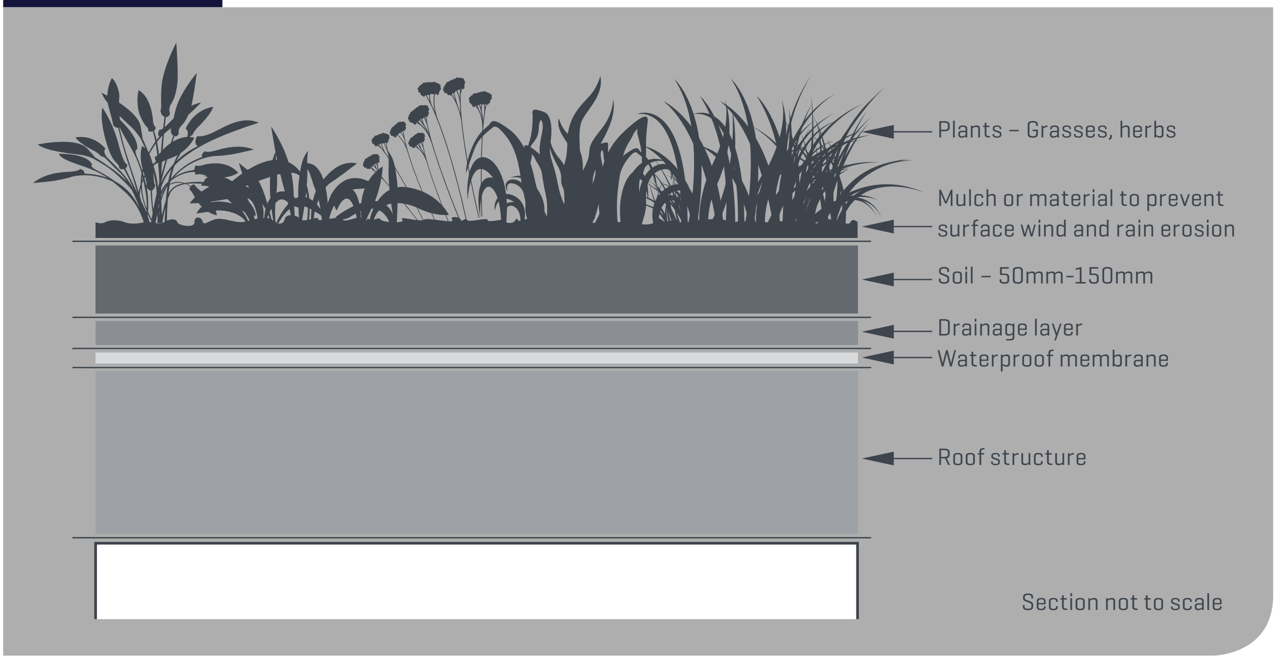
In the following sections further discussion will be focussed on green roof and permeable paving technology only. This is due to the fact that rain gardens, although a viable option, have more stringent requirements than permeable paving to treat similar spaces and treatment trains are a combination of the other approaches.

3.1.2 Construction technologies and technical features for Green Roofs

What is a 'green roof'? It can defined as a roof that uses plants which range from but do not exclusively include grass, moss, lichen, sedum, trees, shrubs, flowers and bushes. Green roofs are referred to by a number of different labels, such as eco-roofs, nature roofs or roof greening systems. In summary green roofs are a living vegetated roofing alternative to traditional impervious roofing materials. A green roof is comprised of the following components: a roof structure; a waterproof membrane or vapour control layer; insulation (i.e. if the building is heated or cooled); a root barrier to protect the membrane (i.e. made of gravel, impervious concrete, polyvinylchloride (PVC), thermoplastic polyolefin (TPO), high-density polyethylene (HDPE or copper); a drainage system; a filter cloth (non-biodegradable fabric); a growing medium (soil) consisting of inorganic matter, organic material (straw, peat, wood, grass, sawdust) and air; and plants. See figure 5 for a typical green roof cross-section.

Green roofs may be either intensive or extensive. Intensive green roofs are better known as 'roof gardens' and typically provide space for people. The depth of soil or substrate layer provided is usually greater than 150 mm and requires artificial irrigation. Extensive roofs require a planting medium of less than 150 mm and are usually designed to require minimal maintenance and to obviate the need for irrigation. The attributes of the two types are shown in Table 1. There is a third type, a semi intensive green roof which is a hybrid of the intensive and extensive roofs. It is vital to keep the plants alive in the long-term and this is a challenge because it requires an active and ongoing commitment to a maintenance and irrigation or watering regime (Skyring 2007; Munby, 2005). Standard soils are not used because they are too heavy for roof structures and a calculated ratio of aggregate (e.g. shale, vermiculite), organic materials, air and water is used. The correct growing medium is critical and may be challenging in some Australian cities due to climatic conditions particularly excessive seasonal rainfall (e.g. as in the Northern Territory or Australia) or minimal rainfall (e.g. as in Victoria).

Figure 5 **Typical green roof section**



Source: www.landcareresearch.co.nz/research

Table 1 **Attributes of extensive and intensive green roofs**

Extensive green roof	Intensive green roof
Shallow growing medium (<150mm)	Deeper growing medium (>150mm)
Lightweight structure to support roof	Heavier roof structure required to support roof
Cover large expanses of rooftop	Small trees and shrubs feature
Requires minimum maintenance	More maintenance required
Lower capital cost	More expensive
Not usually recreational	More common in tropical climates
Accessible or inaccessible	Accessible or inaccessible
Does not usually require irrigation	Requires irrigation
Minimum structural implications for existing buildings	

Source: Wilkinson and Reed, 2009

The literature shows that the suitability of an existing building for a green roof retrofit is dependent on a number of factors such as the roof type, size and slope. Clearly the construction of the roof structure and roof covering influence the type of green roof that may be retrofitted, for example the load-bearing capacity of the structural form. Roofs on mid-sized and large commercial buildings in both the UK and Australia tend to have concrete slab construction. However many commercial buildings in Australia have a timber roof structure covered with profiled metal sheeting which is less able to bear heavy loads and this roof structure is not considered suitable for green retrofit within this study. Furthermore depending on the intended use of the roof the size of the roof is an issue, for example; is either public or building user access possible or desirable for a recreational green roof? The roof may be too small to warrant the cost of the work to retrofit. It is also possible other remedial works, such as upgrading access is required, and this renders the project prohibitively expensive compared to the final overall benefit gained.

Extensive and intensive green roofs require a minimum slope of 2% and green roofs with less than 2% slope require additional drainage measures to avoid water logging (University of Florida, 2008). Additional requirements include good drainage and waterproofing. Depending on the structural load bearing capacity of the existing roof, a lightweight growth media and additional structural support may be required. In Australia the capacity for rainwater harvesting and the use of drought or heat tolerant plants is desirable to cope with fluctuations in climate. Furthermore some roofs have a water supply whereas others do not, and this is an issue where watering and irrigation of plants is required as it can add to the costs. On the other hand biodiversity roofs tend not to have artificial watering, which may be an option if there is no water supply. However biodiversity green roofs can become very dry and brown during summer periods and they may not appeal to some owners on aesthetic considerations. If stormwater attenuation is the design objective of the green roof, the stormwater retention qualities of green roofs depend upon the depth of the substrate and other variables, including: exposure; prevailing wind conditions; the absorbency of the substrate and its water retention qualities; and the amount of evaporation (which varies according to external temperatures and humidity) (Blanc et al., 2012).

Longevity of the structure, drainage and waterproofing system is essential because replacement costs are high. Green roofs can be designed to last over 50 years (Porsche and Köhler, 2003) which is approximately twice the life cycle of a roof covering such as bitumen (Claus and Rousseau, 2010) and on this basis may present a good economic argument for installation. Where an existing roof covering is approaching the end of its useful life, it may be opportune to retrofit. Overall the following criteria are taken into account when determining whether a roof is suitable for retrofitting: position of the building, location, orientation of the roof, height above ground, pitch, weight limitations of the building, preferred planting, sustainability of components and levels of maintenance. The first six criteria are physical attributes of buildings and the last three are related to building owner and/or client desires and the ability to maintain the green roof.

Other decision considerations

In addition, other factors influence the potential to retrofit a green roof. For example, climate affects the type of green roof it is possible to provide and Australia, which has eight climate zones within its national boundary, is one of the most climatically diverse nations. A green roof solution for Adelaide will be very different from a green roof design in Darwin. The UK has less diverse weather conditions but the location of Britain on the edges of two continental climate systems makes for very unpredictable weather patterns.

Owners and/or property / facility managers need to consider maintenance requirements. Long-term maintenance is essential and a minimum five year maintenance contract is recommended to ensure the correct processes are undertaken and that planting is properly established. Maintenance requirements will vary depending on the type of roof provided, such as biodiversity, stormwater, aesthetic or food producing. All green roof types will have variable water retention characteristics which will also vary depending on their location, orientation and exposure. Roofs designed for stormwater retention should have enhanced water absorption qualities. Finally there is the budget to consider, which includes how much is the building owner willing to pay for a green roof. A whole life cycle costing approach may be useful to determine the overall costs and may offset a higher initial construction and installation costs.

Another influencing factor is the local weather conditions with regards to water availability. In Australia rainfall is very variable, for example, during the 2000s in Melbourne and throughout many regions in Australia there was an ongoing drought for a decade, when extremely low levels of precipitation would ensure that growing vegetation on green roofs would be challenging. It could be argued that more water would be drawn out of the main system to maintain planting, thereby further diminishing already low stocks. If buildings were simultaneously fitted with grey-water recycling systems then previously lost water could be diverted to rooftop roofing systems and green roofs might be viable. However this option may place a further cost burden on owners. Conversely in the early 2010s there have been a number of flash floods in the CBD, notably in March and December 2010, February 2011 and June 2012, where stormwater systems were overwhelmed.

Research conducted by Povell and Eley (cited in Markus, 1979) and Isaac (cited in Baird et al., 1996) noted that the number of site boundaries (i.e. whether a building is adjoined to another or others) determines the ease of green roof retrofit. Buildings which are not attached to others tended to be easier to adapt because of access and the lack of disturbance caused to neighbours (Kincaid, 2003). Table 2 summarises the technical features to be considered.

Table 2 Technical Features for Green Roofs

1.	Position of the building
2.	Location of the building
3.	Orientation of the roof
4.	Amount of overshadowing (if any)
5.	Roof type
6.	Roof size
7.	Roof pitch / slope (2%+)
8.	Load-bearing capacity
9.	Drainage and waterproofing system
10.	Condition of the existing membrane
11.	Access to the roof for construction and user (if accessible to users)
12.	Weight of substrate and planting
13.	Water supply
14.	Preferred planting
15.	Levels of maintenance desired

Source: Wilkinson and Reed, 2009

3.1.3 Construction technologies and technical features for Permeable Paving

Proper design of permeable paving will require the guidance of structural and geotechnical experts. For initial identification of potential sites, it is useful to have some broad filtering guidelines that indicate whether a site may be suitable for permeable paving. Technical design considerations that limit the installation of permeable pavements include the consideration of whether the sub-surface water flows will cause problems for surrounding assets or soil or slope stability. Authors have suggested setback of 3m downhill from buildings and 30m uphill if no liner is used (District of Columbia, 2013). The use of a liner and permeable under-drain can be helpful in reducing the impact on adjacent foundations but reduces the in situ infiltration capacity. The type of soil and its permeability is a determinant of whether infiltration will be sufficient to empty the pavement reservoir or whether an under-drain or pumping will be needed.

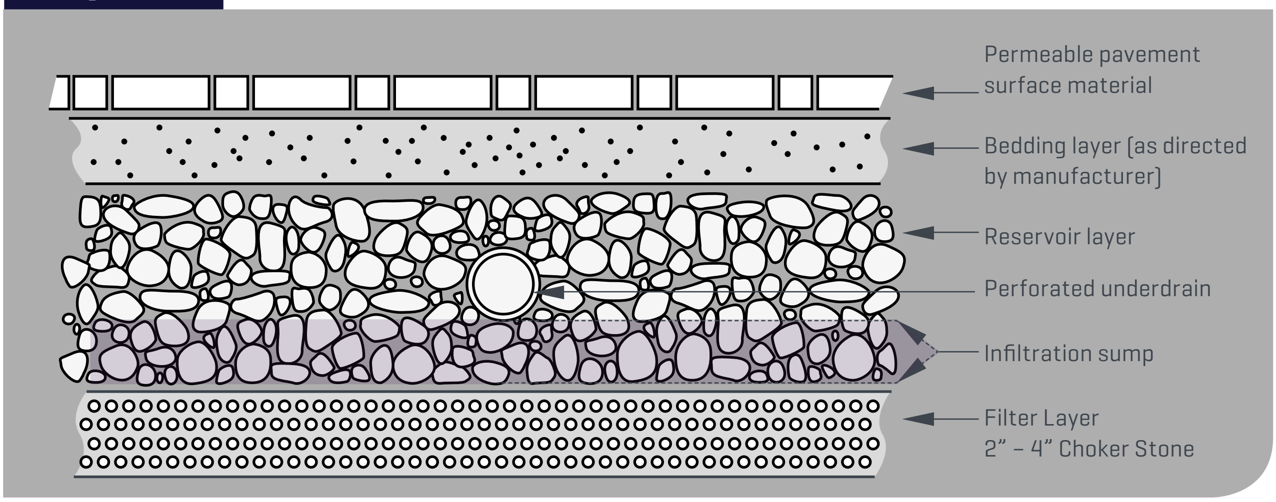
Water quality considerations are important in the choice of systems designed to infiltrate and therefore permeable pavement is not recommended in highly polluted areas. Adelaide's WSUD guidance suggests avoiding areas where sediment loads would have the potential to clog the system (Government of South Australia – Greater Adelaide Region, 2010). In areas with high water tables it is recommended to allow 1m below the sub base before the water table is reached (Woods-Ballard et al., 2007) in order to avoid ponding and groundwater problems; drained and pumped systems may, however, require smaller clearance. It is also important to avoid disturbing services and this may be problematic within dense urban areas.

Load bearing capacity of different pervious paving will differ but most are not recommended on road areas bearing heavy traffic loads (Woods-Ballard et al., 2007; Government of South Australia, 2010). In frost-prone areas deterioration can be avoided by ensuring the design storm does not result in water standing in the asphalt layer.

The consideration of sloping sites is complex. It is advantageous in infiltrating systems to have the base of the paving as flat as possible to encourage even infiltration. If the upper surface is too sloped this can result in water from higher reaches being discharged further down the slope. Therefore it is important to have slopes as small as possible or to step systems. In both the UK and Australia, the recommended maximum slope is 1 in 20 (5%) (Interpave, 2010; HydroCon Australasia Pty Ltd, undated); the reason being that for slopes greater than this, water from heavy rain events travels rapidly over the surface of the pavement, instead of infiltrating as intended. Gradients of as little as 3% have, however, been said to be problematic (District of Columbia, 2013). Surrounding topography also needs to be considered as the infiltration of run-on surface water will affect the capacity of the reservoir to contain design storms. In order not to overload the system in sloped areas it is not recommended to drain water into permeable paving section from an impermeable area any more than 5 times its size (District of Columbia, 2013).

Design variants for permeable surfacing include: porous asphalt (PA); pervious concrete (PC); permeable interlocking concrete pavers (PICP); concrete grid pavers (CGP); plastic grid pavers. These systems are not typically designed to provide stormwater detention of larger storms (e.g. 2-yr, 15-yr), although they may be in some circumstances. The standard design typically has no infiltration sump or water quality filter, though enhanced designs may include underdrains that contain both of these. A cross section through the latter type is shown in Figure 6.

Figure 6 **Cross Section of an Enhanced Permeable Pavement Design with an Underdrain**



Source: District of Columbia, 2013

Table 3 summarises the technical features to be considered.

Table 3 Technical Features for Permeable Paving

1.	Type of paved area, including traffic load
2.	Site slope <5%; terraced design more suited to slopes >3%
3.	Setback requirements
4.	Contributing impermeable drainage area not to exceed 500% permeable area (maximum 200% is recommended)
5.	Water quality in locality
6.	Low sediment loading (high debris loads will clog interstices)
7.	Minimum depth to water table
8.	Permeability of soil (dictates underdrain requirements)
9.	Detention storage required (design storm)
10.	Proximity to utilities
11.	Maintenance considerations (to prevent clogging – eg sand must not be used on permeable to increase traction in icy periods)

Checklists for site inspections are available in Australia and are being developed in the UK (Government of South Australia, 2010; Abbott et al., 2013).

Therefore the factors considered were:

- Type of paved area – in the city centre most roads were considered to be unsuitable due to heavy traffic loads. An estimate of 40% of road area being pedestrianised or under trams will be used.
- Car parks; pavements and roadside; and pedestrian areas and paths were considered suitable.
- Slope of paved area should be less than 5% but slope information was not available so not taken into consideration.
- Setback requirement were ignored because the permeable pavement will be assumed to be lined and under-drained.
- Surrounding drainage area considerations were ignored as slope information was not available.
- Sediment loads were ignored as it was assumed that road sweeping and maintenance is carried out in CBD areas.

3.1.4 Cost benefit

Costs and benefits of sustainable drainage for new development have been widely proposed to be greater than for traditional drainage systems (for example, CIRIA, 2009; Jha et al., 2012). In meeting requirements to limit runoff in the UK, installation of SUDS in new development are becoming more commonplace due to the requirements of the Flood and Water Management Act (2010) whilst in Australia, government policy on water sensitive cities explicitly incorporates these design features (Department of Infrastructure and Transport – Australia, 2011) and this has led to further initiatives at state-level, for example in Victoria (The World Bank, 2010).Therefore it is becoming accepted that the most cost-effective opportunities for SUDS installation arise during new construction and development (for example, Bloomberg and Strickland, 2012a). At present, neither the expertise nor software for designing SUDS is as widely available as that for conventional systems, giving rise to higher design costs in the short term, as noted by Jha et al. (2012). The maintenance costs for well-designed and maintained SUDS can, however, be lower (Duffy et al., 2008; MacMullan and Reich, 2007).

When it comes to retrofit the available evidence for costs and benefits is lower (Stevens and Ogunyoye, 2012a). The availability of data on previous projects, and the complexity of differential expenditure and costs of retrofitting in busy city centres, ensures that each opportunity for retrofit will need to be considered on a case by case basis. Both permeable paving and green roof technology have the potential to be cost beneficial in the retrofit context: on a purely cost based basis Gordon-Walker et al. (2007) found that permeable block paving cost less on a lifecycle basis than regular paving due to the reduction in replacement and maintenance costs. As non-road hard surfaces require replacement on a rolling-programme basis, an opportunity will therefore naturally arise for replacement with permeable alternatives: if half such surfaces in the UK were retrofitted in this manner, the discounted economic benefits could be around £1.7 billion. (Gordon-Walker et al., 2007).Therefore if permeable paving is used to replace traditional paving as part of planned replacement and maintenance a saving should accrue to municipalities, owners and occupiers. Similarly, the lifecycle costs of some types of vegetated roofs have been calculated to be far lower than traditional alternatives such as bitumen and gravel (Porsche and Köhler, 2003); green roofs have been found to aid protection of waterproofing materials from solar damage (Vila et al., 2012; Livingroofs.org, undated).

However by including the benefits of SUDS the potential for green roofs and permeable paving to outperform traditional systems is enhanced. In considering the function of flood risk reduction or stormwater management, against traditional paving and roofing material, there is ample evidence that in some situations the financial case can be compelling. It has been calculated, for example, that widespread adoption of green roofs in Portland, Oregon (USA) could potentially save $60 million of public expenditure otherwise needed to upgrade the extant stormwater system (Bureau of Environmental Services – City of Portland, 2008).

In the United States a national tool has been developed that assesses the cost and benefits of SUDS measures (Center for Neighborhood Technology (CNT), undated) which calculates the monetary value of twenty different benefits of SUDS. These include flood risk reduction, pollutant removal, environmental and amenity benefits; for flood protection, for example, the reduced flow from a site during a 100 year storm event is valued at $1,000 per acre-foot (1,230m3) (or $0.81/m3) based upon flood damage data from US case studies. In the UK there is an ongoing project, coordinated by CIRIA to develop a similar tool. The need to formulate an industry view was demonstrated by previous estimates of the net benefits of sustainable drainage to new developments over a 50 year period would be between £56 million and £5,608 million (Stevens and Ogunyoye, 2012a). This estimate assumed damage per property due to surface water flooding between £23,290 and £29,430, 2% of homes were estimated to be at risk of flooding from surface water, and the number of homes susceptible to flooding was taken to be between 2.8 million and 3.8 million.

Design aspects can be important in changing the cost benefit equation, extensive green roof installation is the lowest cost option in many cases but may not be the optimum choice for stormwater management: for example, the Beijing Olympic Village (China) had some green roofs included at constructions, but Jia et al. (2012) calculated that improvements could be achieved if the substrate depths were doubled from 0.3 to 0.6m. This modification optimised predicted outcomes in terms of maximising the flood control benefit whilst minimising cost. Different types of permeable paving incur variable costs of installation and maintenance and may be chosen for aesthetic as well as practical reasons.

SUDS methods can, however, provide a range of environmental and amenity benefits that are lacking in conventional systems and these are typically uncosted, as discussed by MacMullan and Reich (2007) and are discussed below.

A further complicating factor for the assessment of costs and benefits in urban areas relate to the disparity between who pays for the measures and who benefits from them (Abbott et al., 2013). This is relevant within the storm-water and flooding aspects of SUDS costs and benefits, as the owner of a green roofed building or permeable paved area provides reduced runoff to neighbouring properties. However, when the multiple additional benefits of SUDS are considered, the number of direct and indirect beneficiaries increases. This is further discussed in section 3.4.

3.1.5 Other benefits

SUDS installation can benefit not only the property owners, but also the wider community and the environment itself. For example, a regeneration project in Malmo (Sweden) was initially driven by flood risk management concerns (Kazmierczak and Carter, 2010), but it was subsequently found that the creation of green infrastructure not only improved the neighbourhood aesthetically but also benefitted its overall reputation. Flood mitigation may extend beyond the property adopting these measures, whilst amenity benefits accrue to local businesses, residents and visitors to the urban area. The apportionment of costs and benefits for green infrastructure is an area that warrants increased research attention, in order to support improved implementation procedures.

The additional benefits associated with green roofs include thermal buffering of buildings; this can lead to reduced need for heating in winter and cooling in summer, and therefore lower energy costs for the inhabitants (for example, Fioretti et al., 2010; Bastien et al., 2011). Yang (2008) found that green roofs improved air quality in the urban canyon. Retrofitting with green roofs on a large scale could reduce the urban heat island effect whereby temperatures are typically up to five degrees higher than the surrounding suburbs (Williams et al., 2010). By protecting waterproofing materials from solar damage, a reduction in maintenance costs can be demonstrated (Livingroofs.org, undated). Getter and Rowe (2009) calculated that, if the city of Detroit (USA) greened 15,000 hectares of rooftop, over 55,000 tonnes of carbon could be sequestered. Other examples are the mitigation of urban heat island effect and improved air quality (Bureau of Environmental Services – City of Portland, 2008); improved biodiversity (for example, Livingroofs.org, 2005); and the reduced risk of pollution and stream degradation (Carter and Rasmussen, 2006). Similarly, where drainage authorities charge for runoff entering piped systems, property owners who retrofit permeable surfacing may benefit from reduced fees; the benefits for the environment are chiefly in terms of the reduced pollutant load entering watercourses.

There are very strong environmental sustainability benefits of retrofit (Douglas, 2006). Particularly the retention of existing carbon, as well as cost benefits derived through lower operational costs achieved through energy savings (Bullen, 2007). Building demolition is a waste of resources that typically end up in landfill (Wilkinson 2011). Storm-water run-off may be reduced through green roof retrofit and rainwater harvesting may be employed to reduce potable water consumption for toilet flushing, clothes washing and garden watering. The economic benefits are that retrofit is cheaper than new build if the construction form is straightforward (Bullen, 2007) and that costs of finance tend to be lower as the building may remain occupied during retrofit (Highfield, 2000). However where the build quality is poor, costs may be more expensive (Bullen, 2007).

Economically property values are enhanced with retrofit projects (Chau, 2003) and a further advantage of green roof retrofit, is that maintenance costs are reduced and new employment opportunities created. Table 4 summarises these other benefits.

Social sustainability is important, though challenging to measure and compare to economic and environmental benefits. The social sustainability benefits of retrofit include the retention of existing structures familiar to the local community (Bromley et al., 2005). Often retrofit exists as part of urban regeneration and allows development of the new alongside the old (Bullen, 2007). However retrofit is not always possible or desirable especially where it is not possible to achieve the standards required in contemporary legislation. Another social benefit from a retrofitted green roof is the perception of a closer relationship to the natural world, known as the 'biophilia phenomenon' (Kellert and Wilson, 1993). In commercial buildings there are studies which examine user satisfaction and worker productivity and which aspects of office building design are valued by the users (Wilkinson et al., 2011). Some studies have concluded that proximity to nature plays an important part in satisfaction with the environment generally. Other studies on sustainable buildings and POE have concluded that productivity is increased on the basis that less work days are lost through absenteeism (Keeling et al., 2012). Finally the aesthetics of the roof may be enhanced through green roof retrofit.

Table 4 **Other benefits of retrofitting green roofs**

1.	Reputational enhancement for suburbs / areas /projects
2.	Aesthetic improvements
3.	Flood mitigation
4.	Thermal buffering of buildings
5.	Reduced maintenance costs
6.	Carbon sequestration
7.	Reduction in urban heat island
8.	Improved air quality
9.	Improved bio-diversity and nature conservation
10.	Reduced risk of pollution and stream degradation
11.	Reduced fees for property owners where there is a charge for runoff into streams
12.	Increased energy efficiency of buildings and lower carbon GHG emissions
13.	Retention of familiar landmarks and buildings
14.	Closer relationship and access to nature for urban populations (biophilia effect)
15.	Enhanced user satisfaction and worker productivity for commercial stock
16.	Retrofit is cheaper than new build
17.	Rain-water harvesting opportunity can reduce use of potable water
18.	Cost of finance for retrofit is often cheaper as building remains occupied
19.	Property values enhanced
20.	Possibility of growing food crops where intensive roof type suitable – particularly vegetables and fruit
21.	New employment opportunities created

Figure 7 **Overviews of the building styles in Newcastle upon Tyne's CBD (left) and Melbourne (right)**

Source: J. Lamond

3.2 Retrofit potential Databases

The CBDs of the cities of Melbourne (Australia) and Newcastle upon Tyne (UK) were found to provide broadly similar locations for the study. Both were originally laid out in the 1830s; the 'Hoddle Grid' in Melbourne and 'Grainger Town' in Newcastle both incorporate a mix of historically important architecture interspersed with more modern buildings (see Figure 5) and both cities lie on the sloping land on the banks of major navigable watercourses. Both cities have also undergone extensive expansion over time, with once-permeable agricultural land on the outskirts being replaced by suburbs featuring largely impermeable surfaces; in each case, the CBD includes streets constructed over culverted watercourses (notably Elizabeth Street, Melbourne and Grey Street/Dean Street in Newcastle). Culverts are not only prone to collapse and blockages but, even when functioning correctly, in extreme rainfall events the volume of water can rapidly exceed the carrying capacity, giving rise to localised flooding. These events typically take residents and business-owners by surprise, as the existence of these subterranean watercourses has been lost from local memory (for example, Wilson et al., 2004). Both cities have been affected by pluvial flooding in recent years: this has not emanated from the main rivers (fluvial flooding) but has been predominantly caused by overland flows or 'flash floods'.

In 2012 Newcastle upon Tyne experienced a severe rainfall event in which the whole of the expected total for June (50 mm) fell within a two hour period (Environment Agency – Yorkshire & North East Region Hydrology, 2012) and was estimated as having a 1:131 year return period, also called Average Recurrence Interval (ARI). This is a statistical estimate of the average period in years between the occurrences of a flood of a given size or larger; for example, floods with a discharge as large as the 100 year ARI flood event will occur on average once every 100 years. The ARI of an event gives no indication of when a flood of that size will occur next. Around 40% of non-residential properties affected by the flooding were temporarily forced to close, including Newcastle Central railway station which is located in the CBD (Total Research and Technical Services Newcastle City Council, 2013).

Similarly, in early March 2010, the Melbourne area experienced a severe storm during which over 46 mm of rain fell in a single 24 hour period (Bureau of Meteorology (Australia), undated); the average total for that month is around 50 mm. This lead to a number of roads in the CBD

Table 5 Rank Order of Year of Construction for Buildings in Melbourne

Rank order	Year	Number of buildings constructed
1	1945	38
2	1990	19
3	1972	15
4	1991	14
4	1930	14
4	1920	14
7	1973	12
8	1987	10
8	1969	10
8	1960	10

being rendered impassable for several hours; numerous vehicles were inundated; Flinders Street railway station was flooded; and tram services in the area were suspended (Defra, 2009). Further flooding was experienced on the 4th February 2011 when a deluge broke the daily rainfall record with 17 mm falling in the CBD in just 20 minutes (News.com, 2011).

In the context of anticipated climate change, both Australia and the UK are predicted to experience more intense storm events: sudden, large volumes of runoff water are, therefore, likely to cause more frequent overland flow responses (Gill, 2008; Donald and Seeger, 2010). Where redevelopment is planned in an area where drainage infrastructure cannot be upgraded, one of the strategies recommended by Melbourne Water is the adoption of water sensitive urban design (Melbourne Water Corporation, 2007). This would, inevitably, further increase both the disruption and financial damage arising in the CBDs of the cities under consideration here.

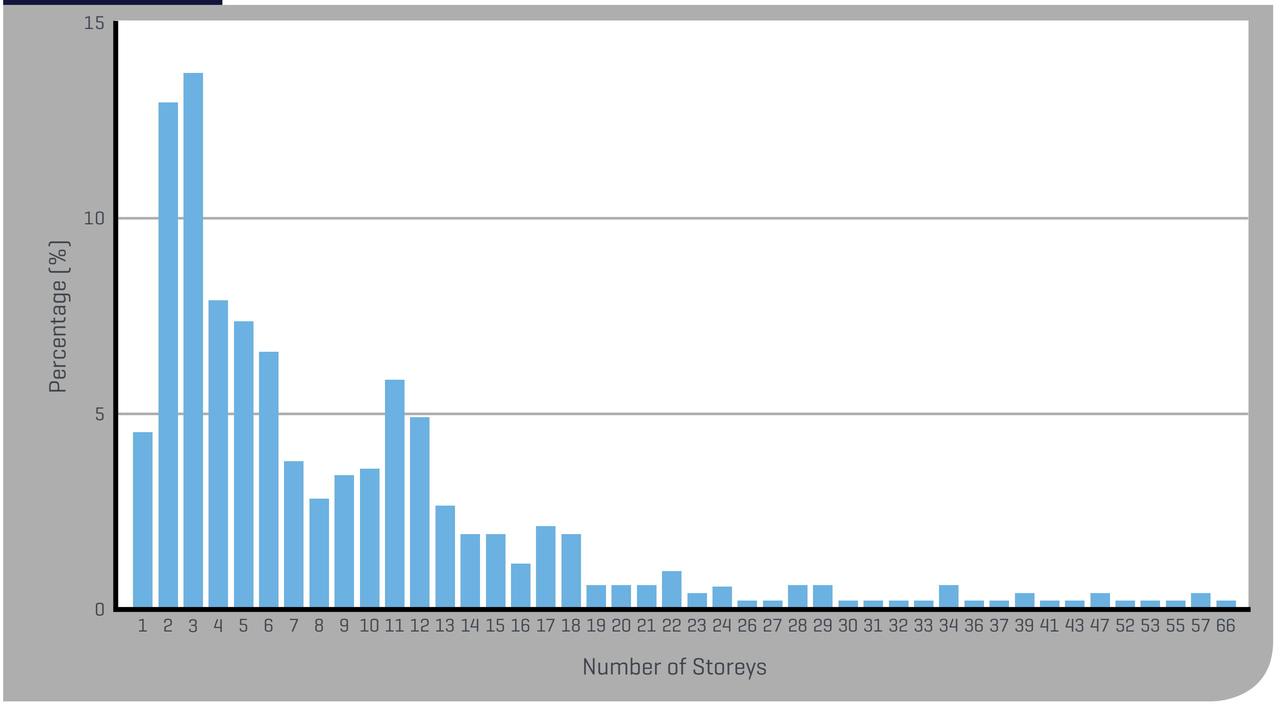
3.2.1 Melbourne CBD Database

This section of the analysis examined 526 CBD buildings in the Melbourne CBD database. The age profile analysis revealed an average age of 61 years, with the oldest building constructed in 1853 and the most recent building erected in 2005. Although some new buildings have been completed since 2005 they were not included in the database which covered the time period from 1850 - 2005. The top ten years for the construction of new buildings are shown in Table 5 and with only two pre-war entries; this reflects the considerable post-war construction in the Melbourne CBD. Between 1940 and 2005 there were 302 (or 60.4%) new commercial buildings built in the city centre.

Minor adaptations were undertaken typically within a 5-7 year period after initial construction, with major works being carried out between 20-25 years probably when the building services required updating and replacement (Jones Lang LaSalle, 2005; Arup Pty Ltd, 2008). Given the high number of Melbourne CBD buildings constructed from the 1960s onwards (237 buildings), there is a large amount of stock which would be due for updating and adaptation and retrofitting green roofs could be considered.

When looking at building height, which is an important issue in green roof technology, the average number of storeys is three and most buildings are low rise and partially or totally overshadowed in many instances. Overall 405 buildings are four storeys high or less and 68.1% of the stock is 10 storeys high or less. The data confirmed that 4.4% of the buildings were between 21 and 30 storeys in height and 2% are 31 to 40 storeys high, 0.8% is 41-50 storeys high and 0.2% was up to 66 storeys high. Figure 6 shows the number of storeys in all buildings and reveals most were in the low to medium rise category. A definition of what is a high rise building is relatively general and refers to metres in height rather than number of storeys. In Australia, the Property Council of Australia uses an office building quality matrix which classes buildings from premium (the highest grade) through to A, B, C and D grades (the lowest grade). Part of the grading criteria is Net Lettable Area (NLA) and not the number of storeys (Property Council of Australia Limited, 2006). According to some definitions, buildings over approximately 7 storeys (or 23 metres high) are in high rise and those over 80 metres or approximately 20 storeys are deemed skyscrapers. Figure 8 shows that a minority of all building have high or sky-rise heights which cast shadows over adjoining lower buildings as the sun moves across the sky during the day. Such an arrangement of buildings could mean that existing buildings which have adequate structural strength to accommodate retrofitting with green roofs may be unsuitable because of overshadowing which adversely affects planting.

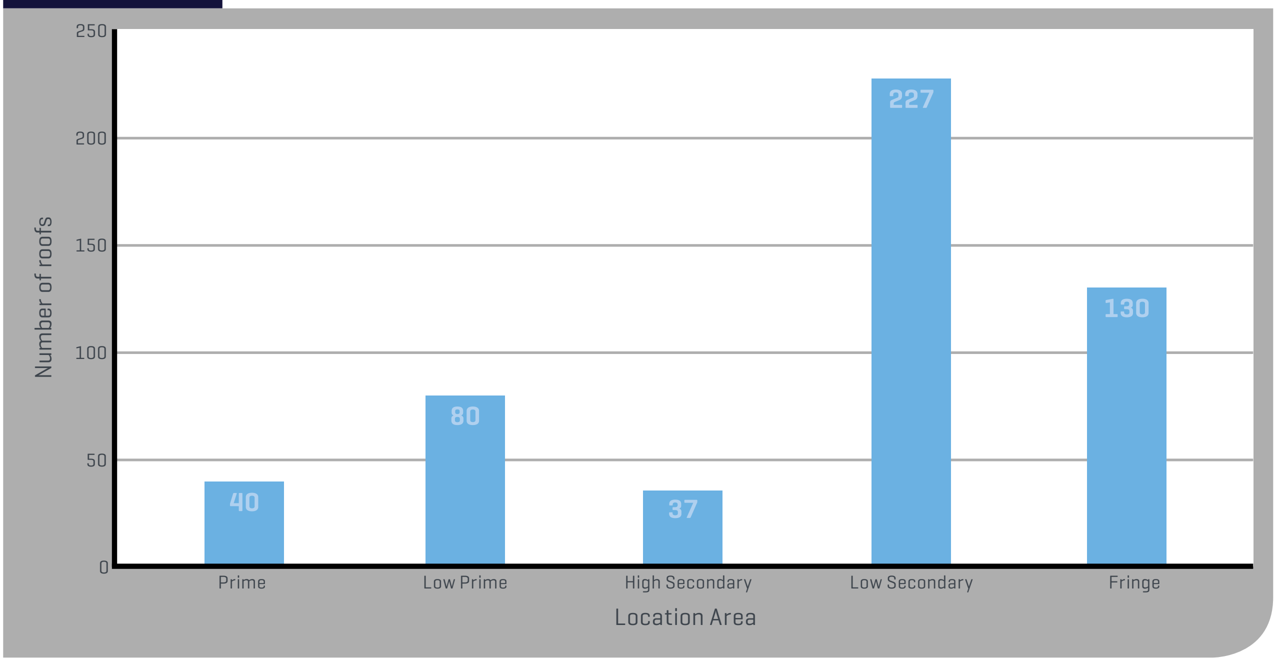
Figure 8 **Number of storeys in Melbourne CBD Buildings**



Source: Wilkinson and Reed, 2009

In the analysis, consideration was given to the site and the location of the building (Kincaid, 2002). Within the Melbourne CBD, locations are categorised as 'prime' (the best location), 'low prime', 'high secondary', 'secondary' and the lowest grade 'fringe. 7.6% were located in the prime zone, 15.2% in the low prime area, and 7% in the high secondary area – thus 29.8% of all properties were located in the higher grade location zones. The highest proportion (43.2%) was is in the low secondary area and nearly a quarter (24.7%) was located in the fringe area at the periphery of the CBD grid. Figure 9 illustrates the distribution of the database properties within the five CBD location zones.

Figure 9 **Distribution of the database properties**



Source: Wilkinson and Reed, 2009

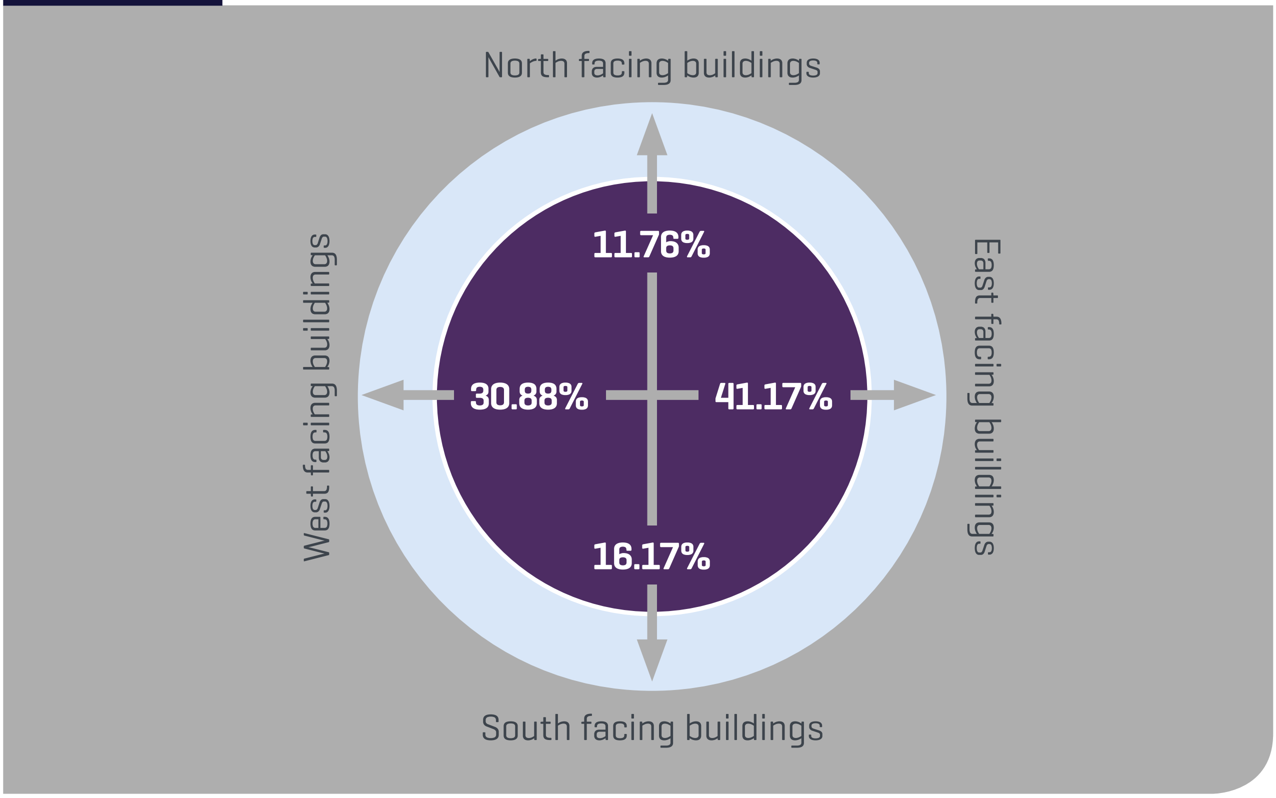
Building orientation determines how much exposure to sunlight the roof gets. In a sample of 72 buildings in the database, an examination of site orientation revealed that most faced east (41.17%) followed by west-facing (30.88%), south-facing (16.17%) and finally north-facing buildings which comprised 11.76% of the sample (see Figure 10). In the southern hemisphere north-facing properties will be exposed the most to the direct sun. Therefore it appears that a large number will only have partial exposure to sunlight, even before overshadowing is considered and that this will affect the type of plants specified and/or whether green roof retrofit is viable.

Ease of access for construction is a further consideration in the decision to retrofit a green roof. In the Melbourne CBD sample, the properties were predominantly bounded on two sides (47.4%), with 21.9% bounded on one side only and 18% bounded on three sides. Only 12.1% were bounded on no sides by any properties or free-standing.

Overall most properties in the sample were not affected adversely by attachment to other buildings or restricted access for construction works, and are therefore suited for retrofitting.

As discussed the structural capacity of the building affects the degree to which, and also the ease of retrofit. Overall 60.6% of commercial buildings in the Melbourne CBD have framed structures. Concrete framing is preferred over steel frame construction in Melbourne and most buildings are built using concrete. The remaining 39% of the buildings comprised traditional load-bearing brickwork and/or stone construction. It is apparent that the buildings with concrete frames are more likely to be suitable for retrofitting with extensive green roof systems and this analysis confirmed there was good potential for minimal structural changes to be undertaken to most CBD buildings. It should be noted that a full structural appraisal would be required on an individual building basis to determine structural suitability for retrofit and this is a limitation of this research approach.

Figure 10 **Building Orientation in Melbourne CBD**



Source: Wilkinson and Reed, 2009

The next stage of the research involved a visual inspection of the roof using the Google Earth and Google Map software (Google Earth 6.0, 2008) An evaluation of the potential of each roof for retrofitting with green roof technology was undertaken, where the evaluations called for identification as one of three classifications, namely (a) 'yes', (b) 'no' or (c) 'don't know' with regards to retrofitting. The evaluation was based on roof pitch i.e. those pitched above 30 degrees and below 2% were deemed unsuitable. The amount of rooftop plant especially equipment which vents air from the building and the provision of rooftop window cleaning equipment, safety handrails and photovoltaic units was taken into account, where coverage exceeded 40% of roof area the roof was deemed unsuitable for retrofit. Another criterion was roof construction, and lightweight construction was deemed unsuitable. The results in Table 6 show that 15% of the buildings were judged suitable for retrofit with green roof technology. A relatively low 4.8% of buildings were not classed with yes or no, and a significant percentage of 80.2% were not considered suitable for retrofit based on the criteria above.

The final stage involved an analysis of overshadowing of the stock (see Table 7) where orientation and the proximity of other taller buildings were taken into account. The analysis identified that 39.3% of the buildings were overshadowed and 36.3% were partially overshadowed. Only 24.4% were not overshadowed at all. Therefore approximately 75% of the existing Melbourne stock was considered unsuitable for green roof retrofit on the basis that insufficient sunlight reaches the rooftop for planting to flourish.

Table 6 **Green Roof Option**

	Frequency	Percent	Valid Percent	Cumulative Percent
Valid				
Yes	78	14.8	15.0	15.0
No	418	79.5	80.2	95.2
Don't know	25	4.8	4.8	100.0
Total	**521**	**99.0**	**100.0**	
Missing				
System	5	1.0		
Total	**526**	**100.0**		

Source: Wilkinson and Reed, 2009

Table 7 **Overshadowing of Roofs**

	Frequency	Percent	Valid Percent	Cumulative Percent
Valid				
Yes	205	39.0	39.3	39.3
No	127	24.1	24.4	63.7
Don't know	189	35.9	36.3	100.0
Total	**521**	**99.0**	**100.0**	
Missing				
System	5	1.0		
Total	**526**	**100.0**		

Source: Wilkinson and Reed, 2009

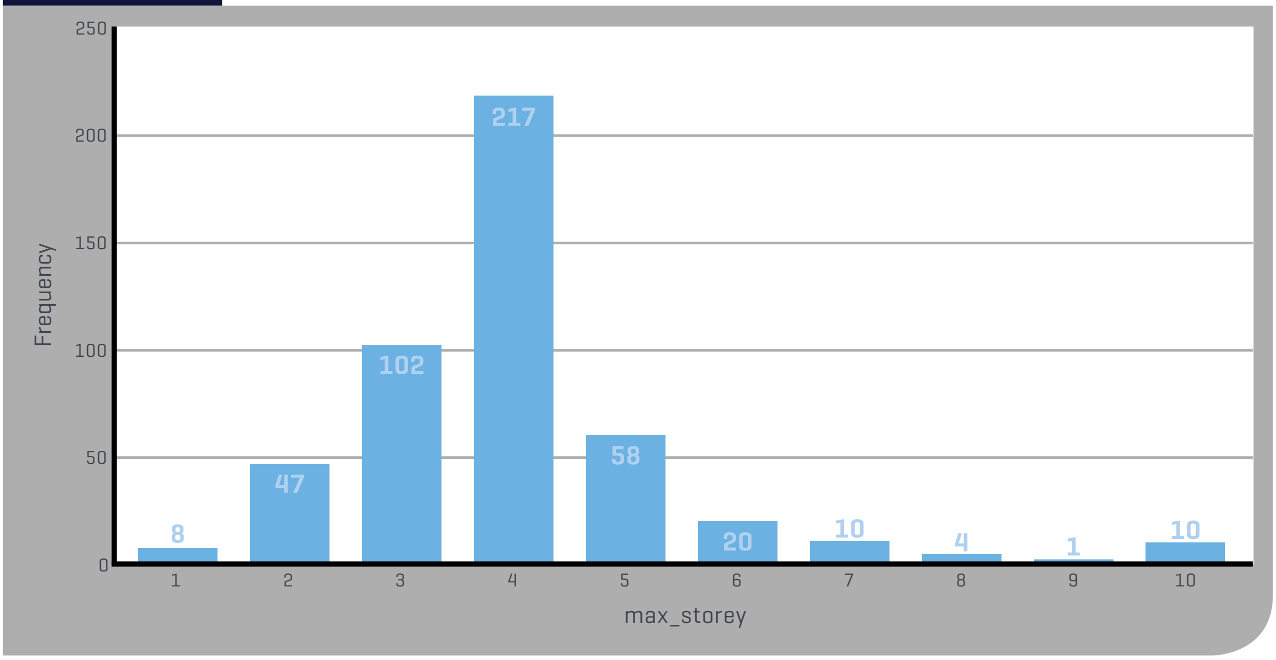
3.2.2 Newcastle upon Tyne UK CBD database

The first section provides an analysis of the 507 buildings in three Postcodes in the Newcastle CBD. The age of buildings was not available for the Newcastle database but the characteristic of the area includes many historic buildings that are listed, with 30 grade 1 and 189 grade 2 listings, and in multiple conservation areas 386 buildings. Clearly the potential to retrofit listed buildings may be limited but it will be important to establish the feasibility of retrofitting on non-listed buildings within the conservation area, as there is also a great deal of more modern development in these areas some constructed as recently as 2012.

When looking at building height the average number of storeys is 4 and the majority of buildings are low rise. However there is a limited potential for overshadowing as there are very few tall buildings in the CBD area studied. Only 2% of buildings were identified as 10 storeys or above and the tallest building has 18 storeys. In the chart below (Figure 11) buildings over 10 storeys are grouped together.

The properties in the Newcastle CBD were predominantly bounded on two sides or more. There were 37.7% bounded on two sides with 30.8% bounded on three sides and 14% bounded on four. Therefore a significant percentage of Newcastle buildings may have site access issues in retrofitting. Nearly half of the buildings (47.3%) have street access only which while it may not make retrofit impossible is likely to add greatly to the cost and inconvenience of building works.

Figure 11 Histogram of building heights in storeys for Newcastle study area



Source: Wilkinson and Reed, 2009

Image source: Markus Gebauer / Shutterstock.com

Table 8 Cross tabulation of conservation area, construction type and historic listing

	Historic Listing status			
	Grade 1	Grade 2	Non listed	Total
Inside conservation area				
Load bearing brick or stone	26	176	136	338
Steel or concrete frame	0	6	20	26
Unknown/other	4	4	14	22
Total	30	186	170	386
Outside conservation area				
Load bearing brick or stone		3	68	71
Steel or concrete frame		0	42	42
Unknown/other		0	5	5
Total		3	115	118
TOTAL				
Load bearing brick or stone	**26**	**179**	**204**	409
Steel or concrete frame	**0**	**6**	**62**	68
Unknown/other	**4**	**4**	**19**	27
Total	30	189	285	504

Table 9 Cross tabulation of pitch and construction type for Newcastle study area

	Constructions type			
	Load bearing brick or stone	Steel or concrete frame	Unknown /other	Total
Roof is of suitable pitch				
Yes	62	48	8	118
No	346	19	5	370
Unknown	1	1	17	19
Total	409	68	30	507

The vast majority of buildings in the study area are load bearing brick or stone (80.7%) with 13.4% steel or concrete frame construction, the rest indeterminate. There was also a strong correlation between construction type, listing and conservation area (see Table 8). This means that the majority of the steel or concrete framed buildings are outside the conservation area and not listed.

From visual inspection of roof pitch it appears that 118 buildings have the slight pitch most suitable for green roof retrofit (see Table 9). Among those with slight pitch about half are steel or concrete with the other half load bearing brick or stone.

Table 10 shows that including historic listing has little impact on the number of potentially suitable rooftops.

Table 10 Cross tabulation of pitch, historic listing and construction type for Newcastle study area

	Constructions type			Total
	Load bearing brick or stone	Steel or concrete frame	Unknown /other	
Pitch of roof OK and building not listed				
Yes	49	45	5	99
No	359	22	8	389
Unknown	1	1	17	19
Total	**409**	**68**	**30**	**507**

Table 11 Table of roofs judged suitable to retrofit based on pitch, historic listing and percent coverage by plant in the Newcastle study area.

	Percent	Valid Percent	Cumulative Percent
Suitable	76	15.0	15.0
Not suitable	410	80.9	95.9
Unknown	21	4.1	100.0
Total	**507**	**100.0**	**100.0**

Table 12 Roofs potentially suitable for intensive green roof retrofit in the Newcastle study area

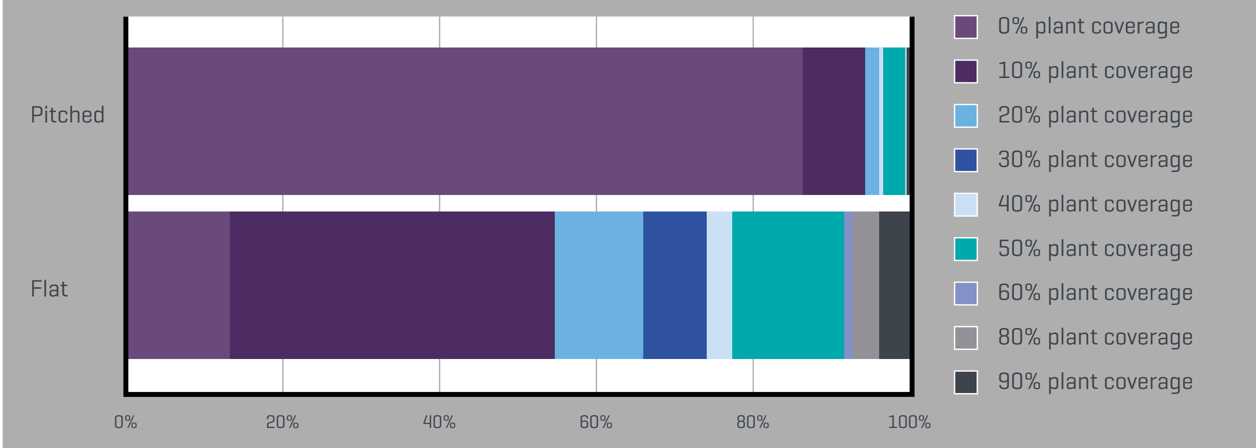
	Frequency	Percent	Valid Percent	Cumulative Percent
Valid				
Yes	20	3.9	3.9	3.9
No	479	94.5	94.5	98.4
Unknown	8	1.6	1.6	100.0
TOTAL	507	100.0	100.0	

Examining the coverage of the roof by plant or car parking spaces further reduces the potential space available for green roof retrofit as shown in Table 11.

Plant was naturally more common on rooftops with low pitch (see Figure 12) and using a cut off point of 40% plant reduces the number of suitable rooftops to 76 representing 15% of the CBD buildings.

If construction type is also considered there are 30 potential retrofit rooftops that could take extra heavy loading and including access and site boundaries brings the number judged suitable down to only 20 as shown in Table 12. Therefore if intensive roofs were considered the potential for retrofit would be less than 4%.

Figure 12 Comparison of proportion of flat and pitched rooftops of varying levels of plant coverage



3.2.3 Comparison

526 office buildings were examined in the Melbourne CBD for their potential for green roof retrofit compared to 507 buildings in Newcastle. The Melbourne stock ranged in age from 9 years to 161 years, with an average age of 61 years, whereas no age data was available for the Newcastle stock. 76.13% was located in conservation areas, with 43.19% listed which suggests the Newcastle stock is older than the Melbourne stock. Melbourne is a new city compared to Newcastle and the CBD was laid out in a grid formation by the military surveyor Robert Hoddle in 1837. Table 13 summarises the main similarities and differences for the two databases.

In terms of height most buildings were low rise; three storeys in Melbourne and four storeys in Newcastle. Melbourne experienced more overshadowing from high rise stock than Newcastle. The highest Newcastle building was 18 storeys high compared to 66 storeys in Melbourne.

Melbourne stock was more likely to be concrete famed whereas load bearing brick and stone construction predominated in the Newcastle stock. The degree of attachment of other buildings affects the ease of retrofit and access for contractors. In Melbourne the buildings were less likely to be attached to others compared to Newcastle where most buildings were attached to others.

Where roof pitched and suitability for retrofit is concerned in both Newcastle and Melbourne 15% of the roofs were deemed suitable.

In summary Melbourne buildings are more likely to be overshadowed but structurally more suited to green roof retrofit. The Newcastle stock is likely to have good exposure to sunlight but less structurally suited to retrofit especially with the heavier types of green roof designs. Despite these differences both cities had 15% of the stock which were found suitable for green roof retrofit.

Table 13 Melbourne and Newcastle Stock compared for green roof retrofit

Green Roof Criteria	Melbourne stock	Newcastle stock
Age	Newer	More listed and older stock
Height	Low rise	Low rise
Overshadowing	Higher levels	Lower levels
Construction type	More suited – more flat concrete roofs	Less suited – more pitched roof construction
Adjoining buildings and accessibility for retrofit	Fewer attached to other buildings	Most attached to other buildings
Percentage of roofs suited	15	15

3.3 Run off modelling and exploration of damage reduction

Estimation of reduced run-off (that is: the reduction in the quantity of surface water that flows off a surface) which results from the retrofitting of SUDS features, is useful for a number of different purposes and at different scales. For example, on an individual building basis the reduction in run-off from a green roof could result in savings in wastewater disposal or it could be used determine the appropriate size for ground level SUDS (Ma et al., 2012). At a city wide level it could be used to determine the reduction in flood hazard and the resultant decrease in expected flood damage (Gordon-Walker et al., 2007). Roof and paved space can represent a high proportion of impermeable surface in urban areas, for example Stovin (2010) links the potential of green roofs to the estimated 40-50% of the impermeable surfaces in urban locations which roofs represent. Thereby these surfaces offer mitigation potential without the need for land-take however the area and location of suitable roofs will have a large influence on the quantity and pattern or attenuation and therefore hazard reduction.

For green roofs, however there are also many other variables that affect the average interception rates both in terms of absorption factors (water is absorbed by the growing medium, thereby delaying the onset of runoff and attenuating peak flows) and release factors (water is released by a combination of evaporation and transpiration, mediated by the foliage) (Mentens et al., 2006). Rose and Lamond's meta-analysis (2013) notes that reported performance ranged from 42-90% of annual rainfall, whilst average retention during storm events varied from 30-100%. Design features including the soil matrix and choice of vegetation can be varied and can affect interception rates by 50-60% on an individual variable. Fixed characteristics such as the geographical location of green roofs have an impact owing to regional climatic variation: vegetated roofs in a sub-tropical Mediterranean climate (for example, Fioretti et al., 2010) will perform differently from those in a temperate maritime climate such as the UK (MacIvor and Lundholm, 2011). In a retrofit scenario, roof characteristics such as overshadowing (which can inhibit vegetation growth) and the degree of pitch of the roof (Wilkinson and Reed, 2009b) may also be fixed characteristics of the urban environment that can impact on run-off reduction.

It follows that for an individual new development installation, where design features, climate and rainfall patterns are known or easy to estimate, fairly specific and precise calculations of run-off are possible. Commercial software is available to aid in the design of SUDS including 'WinDes' (XP Solutions, 2011) and 'Infoworks SD' (Wallingford Software) but these do not explicitly allow for green roof installation. 'SWMM' software does have a green roof modelling feature (US EPA), as does 'xpdrainage'(XP Solutions).

Table 14 Run off calculations for Melbourne and Newcastle showing estimate percentage of total rainfall falling on the CBD managed by potential retrofit under three scenarios

	Assume all roof retrofit		Assume suitable roof retrofit		Assume half of suitable roof and paving retrofit	
	Melbourne	Newcastle	Melbourne	Newcastle	Melbourne	Newcastle
Total Study Area (1000m²)	2150.0	853.0	2150.0	853.0	2150.0	853.0
Area of roof (1000m²)	1150.0	388.0	172.5 (15%)	58.2(15%)	86.3 (7.5%)	29.1 (7.5%)
Area of road (1000m2²)	500.0	226.0	200.0 (40%)	90.4 (40%)	100.0 (20%)	45.2 (20%)
Area of pavement (1000m²)	170.0	131.0	170.0	131.0	85.0	65.5
Run off reduction roof % of total rainfall [1]	32.1	27.3	4.8	4.1	2.4	2.0
Run off reduction road % of total rainfall [2]	23.3	26.5	9.3	4.2	4.7	2.1
Run off reduction pavement % of total rainfall [2]	7.9	15.4	7.9	15.4	4.0	7.7
Total run off reduction %	**63.3**	**69.1**	**22.0**	**23.7**	**11.0**	**11.8**

1 Assume 60% run off reduction over the area of green roof
2 Assume 100% run off reduction over the area of permeable paving but no drainage from adjacent areas

On a larger spatial scale, and in assessing retrofit potential, there will need to be generalised assumptions made about the type and design of green roofs to be retrofitted. Of the two main types of green roof the extensive roof (incorporating shallow rooted species in a relatively thin substrate) is regarded as more suitable for retrofit due to the fact that there will be a lower load-bearing requirement for existing structures. Therefore it is assumed in this study that extensive roof will be the preferred option in modelling run-off. The green roof developers guide for the UK (Groundwork Sheffield, 2011) gives various estimates of retention rate and retention benefits for a green roof. Specifically they place run off percentage in summer as between 50-70% therefore 60% retention is a suitable average figure for estimating run off.

For permeable paving the factors affecting performance are different and relate to the type of paving system installed, the speed of infiltration into the surrounding soil or pumping rate and the design specification of the sub-surface storage. In the UK the major studies examining retrofit potential have made large scale generalisations regarding run-off. For example, Gordon-Walker et al. (2007) used a figure of $0.8m^3$ run off reduction for every m2 of permeable paving. However in this study due to the need to retrofit in dense urban areas with limited infiltration capacity due to soil types it has been assumed that a fully drained system will be used. Therefore 100% retention will be assumed for the permeable paving areas.

Alternatively modelling software and ready reckone rs exist that can assist with specified urban areas. In the US the green values stormwater toolbox is available to examine differences in permeable and impermeable specifications and incorporates soil conditions, typical US rainfall patterns and assumes compliance with US sizing regulations for new development. No such tools exist for the UK or Australia as yet.

To explore run-off reduction in this study therefore the researchers have taken two approaches.

1. To calculate the total potential percentage permeable surface and applied average run-off performance (reported here). Assumptions are that 15% of rooftops, 40% of road areas and 100% of pavements will be suitable for retrofit. The run off retention during peak storm events is assumed to be 60% for green roof and 100% for permeable paving.
2. Use of a state of the art inundation model, as reported in Wilkinson et al. (2014).

The results of analysis 1 are shown in Table 14 and demonstrate that a run-off reduction of 10-20% may be achievable if high levels of potential retrofits are achieved.

Using research from the UK that suggests 10% reduction in run-off to the sewer system has the potential to prevent 90% of flood incidents (Gordon-Walker et al., 2007) this table indicates that retrofit could be a significant mitigation factor for both Newcastle and Melbourne if high levels of retrofit could be achieved. These findings imply that further detailed feasibility studies and modelling are warranted.

Detailed inundation modelling for Melbourne (Wilkinson et al., 2014) and Newcastle (Kilsby and Glenis, 2014) has been carried out by the University of Newcastle upon Tyne. This modelling indicates that due to topographical factors, during extreme events, the surface water flows from outside the CBD study area also need to be taken into account and focussing on the CBD itself may overestimate the potential to mitigate flooding due to rainfall run-off. This is clearly illustrated from the presence of historic culverted watercourses in both Melbourne (Figure 13) clearly showing the presence of the Elizabeth Street drain; and Newcastle (Figure 14) showing multiple river catchments under the wider Newcastle city centre. Therefore it is recommended that a larger study area is used for future detailed audit of retrofit potential for both Melbourne and Newcastle.

Image source: ChameleonsEye / Shutterstock.com

Figure 13 Clarence Woodhouse, Melbourne in 1838 from the Yarra River, c. 1888

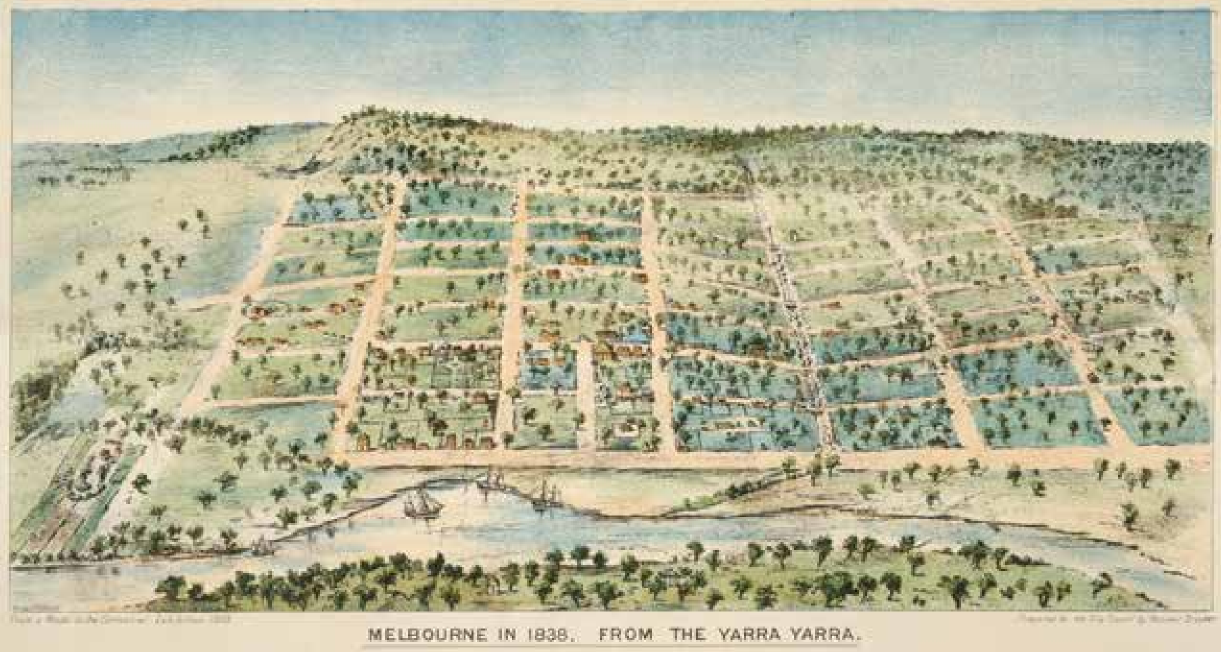


Image source: Courtesy of the State Library of Victoria

Figure 14 Culverting evolution in Newcastle

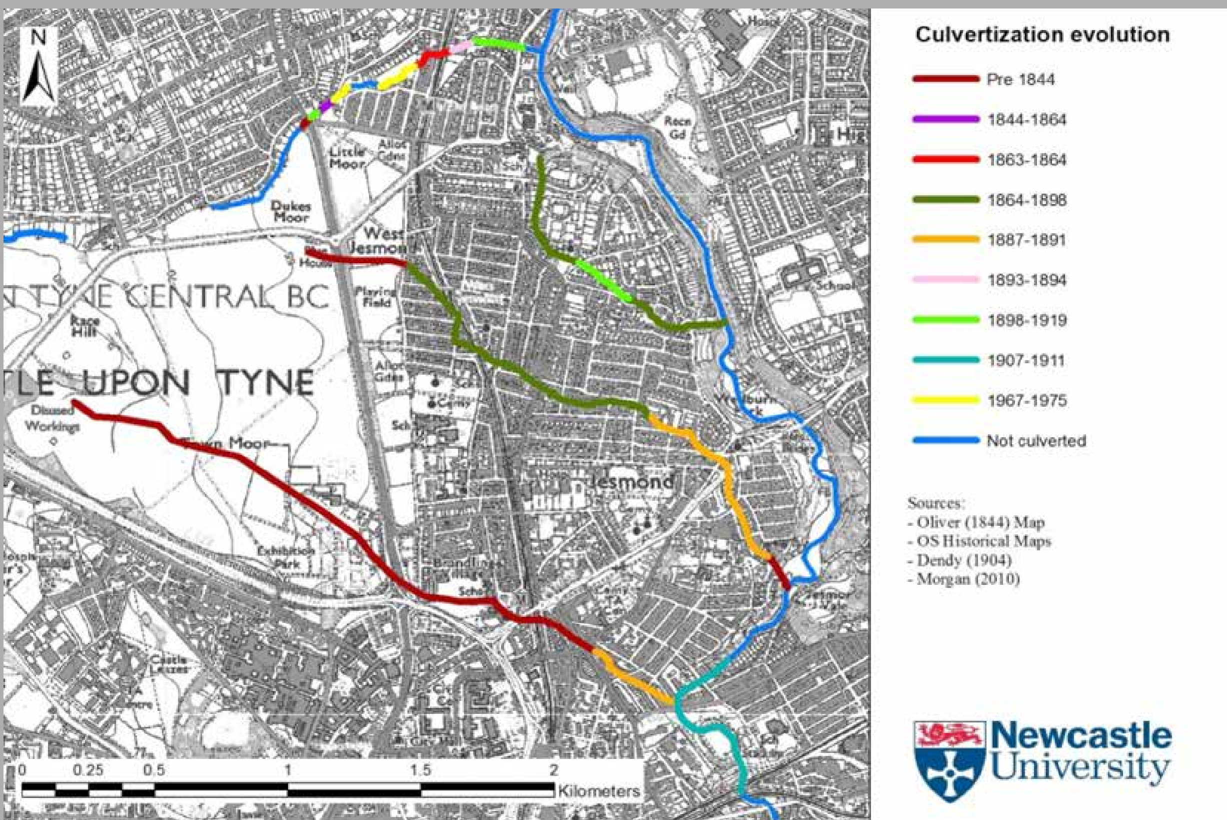


Image source: M Toraldo

3.4 Development of the conceptual model

The literature review generated two key outputs: a list of the perceived benefits of installing green roof technology (as described in the previous section); and a list of stakeholder groups who could potentially be the beneficiaries. The latter includes flood related benefits:

- owners, investors and occupiers of the building to be retrofitted
- customers of the businesses occupying the building to be retrofitted
- owners, occupiers, investors and customers of the other buildings in the vicinity that are at risk from surface water runoff

Non-flood benefits also accrue to some groups, including:

- other local residents, businesses (including employees and customers) – benefit from local environmental impacts
- water companies, their customers and/or municipalities and their ratepayers – benefit from reduced drainage and water processing
- local and national taxpayers, and their representatives – benefit from reduced damage costs
- wider society – benefits from mitigation and broader environmental enhancements.

The cost of the installing a green roof is, however, likely to be incurred by the owner or occupier of the building (unless specific incentive schemes exist); the understanding of the distribution of the benefits across stakeholder groups is, therefore, of key importance as regards the motivation of owners and occupiers of commercial buildings when considering the retrofit of green roofs. Table 15 illustrates how the main stakeholder groups identified from the literature may potentially gain from the installation of a green roof by the owners/occupiers of a given building within the CBD. The two central actors are the building owner/investor and building occupier, as they have a direct interest in the building being considered for retrofit; their decision (to install or not to install a green roof) then affects the other stakeholders as shown.

The list of benefits is also derived from the literature, where evidence has been found that such benefits exist and extends to property stakeholders. Evidence from published sources, however, does not readily lend itself to apportionment of shares of the benefits accruing; furthermore, the majority of these are based on measureable physical aspects of the environment. Benefits can, however, take direct and indirect forms: a direct benefit, for example, would be the reduction of run-off leading to reduced flood risk, both for building occupiers and occupiers of surrounding buildings. An example of an indirect benefit would be the potential for the improved aspect of a commercial property (through the amenity of a green roof) leading to a potential uplift in value (rental or capital).

As the aim of this research is to examine the benefits of retrofitting from the perspective of commercial property owners and occupiers, Table 15 focuses on the indirect benefit flows from their perspectives.

Table 15 Matrix of benefits and beneficiaries from investment in green roof technology

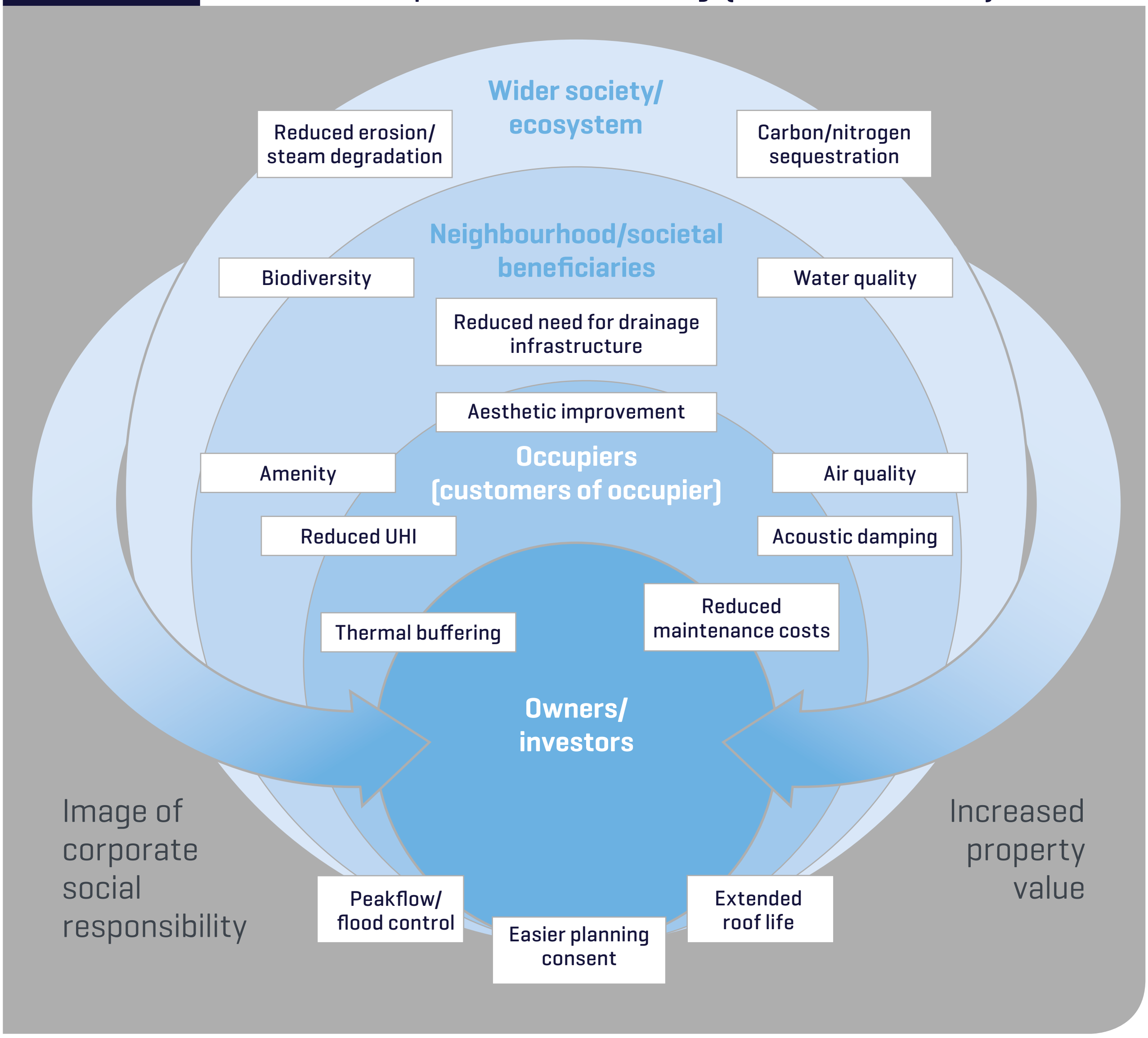
	Building owner/ investor	Building occupier	Those locally at risk from flooding	Local population	Water companies and their customers	Local/national taxpayers	Global benefit/ climate mitigation
Peak flow retention	■	■	■		□	□	
Runoff water quality improvement	▣	□			□	□	■
Carbon and nitrogen sequestration							■
Insulation – reduced heating and cooling	▣	■					■
Aesthetic improvement	▣	■	■	■			
Reduce Urban Heat Island	▣	■	■	■		■	
Acoustic damping		■					
Extended life of roof membrane	□	□					
Biodiversity enhancement	▣	■	■	■			
Lower maintenance costs	■	■					
Amenity Benefit	▣	■	■	■			
Reduced cost of drainage	□	■	□	□	■	□	
Air quality	▣	■	■	■			
Reduced stream degradation	□	□	□	□	□	□	
Reduced land take for runoff reduction vs other methods	■ If runoff reduction required						

■ Beneficiary
□ Potential beneficiary depending on remit of stakeholder
▣ Indirect beneficiary if able to charge higher rents due to neighbourhood improvements

There are, however, additional reputational and operational factors that affect the value of a commercial site to owners and occupiers, as discussed above. The perceived wider benefits (accruing to all stakeholders) therefore feed back into the value of a building (affecting the owners/investors) in ways that are hard to measure and even harder to predict. This is because the value judgements made by the other stakeholders often pertain to perceived, rather than tangible, benefits; the feedback value may, therefore, be unrelated to the scale of measurable impacts, or their distribution among stakeholders. The installation of a green roof may, for example, be seen as socially responsible, as it reduces the urban heat island effect; the benefit of this corporate social responsibility accrues to the owner/occupier, regardless of the actual performance of the roof. The high visibility of a green roof also confers its own advantage, in that immediate neighbours witness pro-environmental behaviour has been undertaken: this is rather more conspicuous than, say, the display of an improved EPC. These considerations have resulted in the development of a conceptual model encompassing both the value of green roof installation to owners and occupiers of a commercial building, and the feedback effects into the company operational profit and building value: this conceptual model is shown in Figure 15. The evidence base necessary to make impact estimates is not yet sufficiently well developed, however, to assign precise quantities to the range of benefits enjoyed by every stakeholder in the conceptual model.

Whilst, in some instances, measureable direct benefits (such as reduced heating and cooling costs) can offset the cost of green roof installation over time, the additional value of energy efficiency may not provide sufficient incentive for retrofitting. Other energy efficiency measures may exist that would be just as effective and less costly. It is equally unlikely that the reduction in flood risk to the individual property on which it is installed would justify the cost of a green roof. This research suggests that the business case for retrofit of green roofs must be predicated on the consideration of multiple direct benefits, as well as recognising feedback from wider societal and ecological beneficiaries. Despite the existence of conceptual and theoretical arguments, the current lack of quantitative studies linking property values, and company profitability, directly to pro-environmental behaviour and company reputation stands as a barrier to such recognition. By identifying approaches that foster understanding of the indirect benefits of retrofitting green roofs, it will be possible to evaluate whether they can drive appropriate adaptation or not.

Figure 15 **Conceptual model of distributed benefits of green roof technology from the perspective of owners and occupiers of commercial buildings (after Abbott et al., 2013)**



4.0 Discussion and Implications/Guidance

Image source: paintings / Shutterstock.com

This work is relevant to all urban centres striving to build resilience to flood events in a cost effective and environmentally sustainable manner. The research compares and contrasts cities in the northern and southern hemispheres, here Newcastle and Melbourne, and therefore assists other urban centres as they plan and implement strategies to mitigate pluvial flood risk. This research complements a great deal of recently completed and ongoing work including RICS work on 'Towards a Low Carbon Built Environment: A Roadmap for Action' (RICS, 2009), 'Redefining Zero'(Sturgis Associates, 2010), and 'Vision for Cities'(RICS, 2010) as well as work undertaken in the UK's ESPRC funded 'RETROFIT 2050' programme (Britnell and Dixon, 2011), 'Delivering and evaluating multiple flood risk benefits in blue green cities' (BlueGreenCities), and CIRIA projects on developing technical guidance for installation of SUDS and WSUD.

The results of this research enable stakeholders such as the Newcastle and City of Melbourne to evaluate the desirability of developing and pursuing incentives to roll out a programme for green roofs and permeable paving in the city for the mitigation of storm-water run-off. The results allow other municipal authorities to reflect on the potential of their stock to accommodate a retrofit programme as part of a strategy to manage risks associated with storm-water flooding. In the process of conducting the analysis there were limited resources to undertake detailed structural appraisals of individual buildings. The remaining building criteria of preferred planting, sustainability of components and levels of maintenance were not considered in depth in this research and therefore represent some of the limitations of this approach. However the implementation of any retrofit programme would require further extensive and detailed evaluation, site inspection and technical analysis on a building by building basis.

4.1 Implications for surveyors

Building surveyors are typically those who are involved with the retrofit of existing buildings and they will need to consider technologies that they are less familiar with, such as green roof retrofit, as they endeavour to deliver sustainability to mitigate predicted climate change and to adapt to those changes. As such they will need to develop methods of appraising whether roofs are suitable for consideration of green roofs and thereafter which type of green roof design is most appropriate for the location and other design considerations such as aesthetics, thermal performance and costs for example. (See section 3.03 above.) An initial green roof retrofit evaluation checklist for Building Surveyors is included in Appendix 1 of this report. The intention is to enable Building Surveyors to consider the relevant factors in an initial appraisal of suitability of a roof and building.

Valuation surveyors will also come across buildings which have green roofs and will need to consider the feature in their appraisal of value. They will need to be aware of the purpose of the roof. For example is it for storm-water, bio-diversity or social recreational space or a combination of these factors? Is it fulfilling its function? What are the annual maintenance costs and requirements for upkeep? If one exists, does it affect the buildings environmental rating? In terms of costs, the green roof will extend the life of the waterproof membrane below the green roof by 100%, so a major repair cost is deferred (Mentens et al, 2006). Valuation surveyors are recommended to refer to other RICS guidance on the valuation of sustainable buildings.

4.2 Areas for further research

This study has highlighted the need for further empirical research into green roof retrofit.

The proposal of a conceptual model for the benefits of retrofitting green roof technology for owners and occupiers of commercial buildings in CBDs is a novel departure from current literature that focuses on the wider societal perspective of reducing flood risk for a district. This research addresses a crucial gap in the implementation strategy of water sensitive urban design, in recognising that the stakeholders most central in enhancing the take up of green roofs may be commercial enterprises or investors that remain to be convinced of the business case for green roofs.

Furthermore, it is critical in this evaluation to consider the full range of benefits accruing from green roof installation, not limited to the flood or water quality issues normally paramount in the cost benefit analysis for local government or environmental agencies.

This research has scoped the associated literature very widely and identified a broad list of actual and perceived benefits from green roofs. The systematic review also identified key stakeholders and beneficiaries of green roof benefits and their proximity to the central actors. Green roofs are seen to have a small potential positive contribution to climate mitigation, but most of the benefits of green roof technology are more direct and relate to quality enhancements in the local environment with the potential to lead to neighbourhood improvement. However, the quantification of the scale and scope of these benefits in CBDs is argued to be in its infancy, therefore further research is needed to fully operationalise the conceptual model with respect to direct benefits of green roofs.

In the context of commercial property it is also important to examine potential indirect benefits of green roofs. Increased operational efficiency within an improved building may boost the utility of the premises for commercial tenants, whilst occupiers of “green” commercial buildings may also benefit from reputational enhancement. Owners and investors could therefore benefit from higher yields from a more attractive commercial environment. Furthermore, the aspect of socially responsible investment could be considered as a reputational gain for these stakeholders. The research suggests that this is not dependant on actual delivery of the technology against perceived benefits, but is based on awareness of green roofs as an ecological good. Therefore this benefit is both locally specific (dependant on cultural norms in the customer base) and neighbourhood and market specific (dependant on the pool of property investors and owners with a vested stake in the business district). The goals and priorities of these stakeholders will have an impact on the willingness to retrofit green roofs.

This insight, together with the lack of monetised benefit data for many of the wider benefits of green roof retrofit, suggests that the complete operationalisation of the proposed conceptual model through robust cost benefit analysis is some way off. Therefore, in discussion of the business case for green roofs in the short term, it may be helpful to consider methodology that allows for the statement and balance of multiple goals, not all of them quantifiable or monetised. Further research is also warranted in order to strengthen the evidence base relating to the actual performance of green roofs in delivering the perceived benefits across the stakeholder groups and their feedback in terms of enhanced property value.

4.3 Signposting of guidance

Best practice guidance regarding the retrofitting of both green roofs and permeable paving has been produced by many organisations in recent years, much of which is available for free downloading. Table 16 lists a broad range of the guidance issued to date in the UK, Australia and elsewhere, but should not be seen as exhaustive; where appropriate the approximate cost of publications is noted. The table categorises the guidance according to the country of origin, the method(s) covered and the focus of the approach, in terms of technical advice, design orientation or a combination of the two. Hyperlinks to the appropriate web sources are provided in the final column.

Table 16 Guidance Sources by country of origin, method, and approach (with hotlinks to source materials)

Originating body/year	Title	Availability	UK	Australia	Other	Green roof	Permeable paving	Technical	Design	Both	Hotlinks
CIRIA 2002	Source control using constructed pervious surfaces. Hydraulic, structural and water quality performance issues	£110.00*	■				■			■	CLICK
CIRIA 2004	Sustainable drainage systems – hydraulic, structural and water quality advice	£156.00*	■			■	■	■			CLICK
CIRIA 2006	Designing for exceedance in urban drainage – good practice	Online	■				■		■		CLICK
CIRIA 2007	The SUDS Manual	£210.00*	■			■	■			■	CLICK
CIRIA 2007	Site handbook for the construction of SUDS	Online	■			■	■			■	CLICK
CIRIA 2007	Building greener – guidance on the use of green roofs, green walls and complementary features on buildings	Online	■			■				■	CLICK
CIRIA 2009	Overview of SuDS performance	Online	■			■	■	■			CLICK
CIRIA 2010	Planning for SuDS – making it happen	£108.00*	■			■	■		■		CLICK
CIRIA 2012	Retrofitting to Manage Surface Water	£180.00*	■			■	■	■			CLICK
CIRIA 2013	Creating water sensitive places – scoping the potential for water sensitive urban design in the UK	Online	■			■	■		■		CLICK
City of Portland 2014	Stormwater Management Manual	Online			■	■	■			■	CLICK
City of Gold Coast 2007	Water Sensitive Urban Design (WSUD) Guidelines – section 13.11 Porous and Permeable Paving	Online		■			■			■	CLICK
City of San Francisco 2010	San Francisco Stormwater Design Guidelines – BMP Factsheets	Online			■		■		■		CLICK
CREW Scotland 2012	Sustainable urban drainage systems (SUDS) and flood management in urban areas	Online	■			■	■	■		■	CLICK
Department for Communities and Local Government and Environment Agency 2008	Guidance on the permeable surfacing of front gardens	Online	■				■		■		CLICK
District of Columbia 2013	Stormwater Management Guidebook – Section 3.4. Permeable Pavement Systems	Online			■		■			■	CLICK
Environmental Protection Agency (USA) 1980	Porous Pavement – Phase 1 – design and operational criteria	Online			■		■			■	CLICK
Environmental Protection Agency (USA) 2008	Managing Wet Weather with Green Infrastructure – Municipal Handbook – Green Streets	Online			■		■		■		CLICK

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Originating body/year	Title	Availability	UK	Australia	Other	Green roof	Permeable paving	Technical	Design	Both	Hotlinks
Environmental Protection Agency (USA) 2011	Green long-term control plan-EZ template: a planning tool for Combined Sewer Overflow control in small communities	Online			■		■		■		CLICK
Government of South Australia 2010	Water Sensitive Urban Design – Technical Manual – Chapter 7 Pervious Pavements	Online		■			■	■			CLICK
Groundwork Sheffield 2011	Green Roof Developer's Guide	Online	■			■			■		CLICK
Groundwork Sheffield/ Environment Agency 2011	GRO Green Roof Code of Best Practice for the UK	Online	■			■				■	CLICK
Institution of Engineers, Australia 2013	ARR Guideline 51e	Online		■			■	■			CLICK
Landscape Institute 2014	Management and maintenance of Sustainable Drainage Systems	Online	■			■	■	■			CLICK
Melbourne Water 2012	Green roofs fact sheet	Online		■			■			■	CLICK
Melbourne Water 2013	Building a planter box raingarden (7th edition)	Online		■		■			■		CLICK
Minnesota Pollution Control Agency 2011	Best Management Practices Construction Costs, Maintenance Costs, and Land Requirements	Online			■		■	■			CLICK
New York City Department of Environmental Protection 2012	Guidelines for the Design and Construction of Stormwater Management Systems	Online			■	■	■		■		CLICK
Nophadrain/Dutch Green Building Council 2012	Extensive green roofs – Design and installation manual	Online			■	■			■		CLICK
Snodgrass 2006	Green roof plants: a resource and planting guide	£20.00**		■		■			■		CLICK
State of Victoria 2014	Growing Green Guide: A guide to green roofs, walls and facades in Melbourne and Victoria, Australia	Online		■		■				■	CLICK
University of Maryland 2011	Permeable Pavement Fact Sheet	Online			■		■			■	CLICK
Victoria BID, London 2013	Green Infrastructure Audit – Best Practice Guide	Online	■				■		■		CLICK
World Bank 2012	Cities and Flooding – Chapter 3 Integrated Flood Risk Management: Structural Measures	Online			■	■	■			■	CLICK

* Prices quoted from the following source, as at 1 April 2014:– any documents described as 'online' are free following registration: http://www.ciria.org/CIRIA/Bookshop/Bookshop/Books/Bookshop.aspx?hkey=5d0b1bf4-bcee-4410-ade0-2dfb2a319cc2

** Price quoted from the following source, as at 1 April 2014: http://www.timberpress.co.uk/books/?search=9780881927870

5.0 Conclusion

Research into the retrofit of sustainable urban drainage in the central business districts is needed because the pressure of increasing urban density and changing weather patterns has led to overwhelming of traditional urban drainage systems, flash flooding and damage and disruption in cities.

The research reported here has considered the potential for retrofit of SUDS features with central business districts to contribute to flood mitigation. Through the extensive review of literature and the detailed analysis of two case study areas it has become apparent that the complexity of evaluation of potential benefits requires a holistic assessment to be made of the multiple features of the urban environment and the specific building under consideration.

Literature reveals that there are examples of SUDS retrofit across many countries that have been pursued for purposes including storm-water or flood management but also to benefit from associated advantages such as reduced wastewater processing charges, improved insulation, lower maintenance costs and reduction of the urban heat island.

The most appropriate SUDS features for retrofit within dense CBD areas are seen to be green roofs, permeable paving, rainwater gardens and small treatment trains. Within the city of Melbourne, green roofs are especially attractive in respect of the urban canyon effect and flood mitigation impacts may be of lesser concern. However it is also observed that the evaluation of multiple benefits can assist in making an economic case for green roof and other vegetated SUDS. Conversely permeable paving is seen primarily as a stormwater control mechanism with fewer associated advantages.

The literature also reveals requirements for the feasibility and performance of green roofs and permeable paving that need to be considered at the stage of option design in order to avoid over estimating the potential to retrofit SUDS features. There are some minimum technical requirements to be met for the lightest and simplest extensive green roofs but other types of roof may be preferred and have more stringent requirements. It is important to design each green roof to meet clearly defined goals and these will differ depending on the climate, location and height of the building among other things.

Depending on various assumptions the database analysis of buildings within two CBDs one in Australia and the other in the UK revealed that the proportion of CBD buildings with potential for retrofit is fairly low. Estimation of other surfaces potentially suitable for permeable retrofit in busy business districts also reveals that a large proportion of urban hard surface may be unsuitable for standard permeable paving systems due to heavy traffic loads.

Estimation of the run-off reduction potential under these assumptions for these two cases study areas can be seen to be realistically around 10-20%, however this can still make a significant contribution to storm-water reduction and peak attenuation. For both of the case study sites however it was seen to be necessary to consider the wider catchment area due to the presence of historic culverted watercourses and topographical features.

On an individual building basis the decision process to invest or not to invest in green roof technology may be influenced by the perceived costs and benefits accruing to owners and occupiers of commercial buildings. A novel conceptual model has been developed that suggests the consideration of feedback from distributed benefits of green roof technology and permeable paving through property value and reputational gains may be highly influential in the decision to invest.

Finally the research has revealed that multiple initiatives and research projects are ongoing in this rapidly developing field. This is partly driven by the UK Flood and Water Management Act 2010 and upcoming regulation in the sector for run-off control in new developments. New tools are being developed, guidance documents published and installations of green roofs and permeable paving are increasing. Therefore these recent documents are summarised in the report for the convenience of professionals who may want to explore the topic further.

Further research is recommended in the measurement and attribution of costs and benefits of green roofs, specifically in the valuation of multiple benefits and the operationalisation of the conceptual model. Further research is also needed on the performance of sustainable drainage systems under a variety of locational, climate and antecedent conditions both in terms of storm-water management and other benefits.

Guidance notes and checklists specifically for scoping potential integrated retrofit projects for commercial property surveyors are recommended and could be developed in the light of recent and ongoing research.

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7.0 Appendix

Checklist for Building Surveyors to appraise roofs for suitability for green roof retrofit

Green roof retrofit checklist

This checklist is designed for building surveyors to use in an **initial appraisal** of an existing building for green roof retrofit:

Please review the following aspects and take into account in your decision making.

1. Position of the building

What is the position of the building within the settlement? Is it overshadowed by other adjoining buildings which may affect access to sunlight and the growth of plants?

- [ ] Not overshadowed (good)
- [ ] Partly overshadowed (maybe OK)
- [ ] Overshadowed (may not be OK)

What is the quality of the building? For example those with a high quality may experience an increase in capital value and yield as a result of having sustainability features such as a green roof.

- [ ] High quality (in Australia PCA Grade Premium and A) – more likely to enhance value
- [ ] Medium quality – may enhance value
- [ ] Low quality – unlikely to enhance value

2. Location of the building

What is the prevailing climatic condition? For example, is the building in a hot arid climate zone or a maritime zone? Each has different characteristics which favour different types of green roof solution. For example, those locations which experience heavy rainfall may favour a stormwater solution aimed to reduce as much runoff as possible.

The prevailing climate is ______________________________

The building and roof location is exposed to

- [ ] High winds
- [ ] Medium winds
- [ ] Low winds

The building and roof location is exposed to

- [ ] High rainfall
- [ ] Medium rainfall
- [ ] Low rainfall
- [ ] Wide seasonal variation in rainfall

Does the location favour; (tick all which apply and rank in order of preference)

- ☐ Stormwater design
- ☐ Improving water quality entering sewer system
- ☐ Thermal design
- ☐ Reducing urban heat island
- ☐ Reducing noise pollution
- ☐ Bio diversity design
- ☐ Aesthetic and social space design

3. Orientation of the roof

North facing is good in the southern hemisphere, whereas south facing is better in the northern hemisphere.
What is the orientation of the roof?

- ☐ Good
- ☐ OK
- ☐ Poor

4. Height above ground

How high is the building? In some locations high buildings are subject to high winds, and or fierce heat which can make growing plants challenging.

- ☐ How high is the roof? ____________ floors

5. Roof pitch

What is the roof pitch?

- ☐ Up to 21 degrees is suited to green roof retrofit
- ☐ exceeding 22 degrees are too steep and not suited
- ☐ minimum roof pitch less than 3 degrees

6. Existing roof construction

What is the existing structural form of the roof?

- ☐ Timber (size and spacing of beams) ____________
- ☐ Concrete slab (depth in mm) ____________
- ☐ Structural steel (size and spacing of beams) ____________
- ☐ Other (describe) ____________

7. Load limitations of the building

What is the dead load bearing capacity of the existing roof? ____________

What is the live load capacity of the existing roof? ____________

8. Preferred planting options

What is the budget?

- [ ] High
- [ ] Medium
- [ ] Low

How much maintenance is available for the green roof plants?

- [ ] High
- [ ] Medium
- [ ] Low

Is there a water supply on the roof?

- [ ] Yes
- [ ] No

Is there a power supply to the roof?

- [ ] Yes
- [ ] No

Are there any potential environmental hazards?

- [ ] Yes
- [ ] No

9. Presence of plant and other equipment on the roof.

The presence of plant such as air conditioning or HVAC may affect plant growth by creating micro-climates on the roof top through the discharge of fumes and warm air.

There is HVAC equipment on the roof

- [ ] Yes (please indicate approximate area covered in M2) ____________________
- [ ] No

There is window cleaning tracks on the roof

- [ ] Yes
- [ ] No
- [ ] Partly

Is there a safety guardrail around the roof? (please indicate) ____________________

- [ ] Yes
- [ ] No
- [ ] Partly

Are there any PV Panels mounted on the roof? (please indicate) ____________________

- [ ] Yes (please indicate approximate area covered in M^2) ____________________
- [ ] No

There is other equipment on the roof which affect the area which could be retrofitted (please indicate)

____

- [ ] Yes (please indicate type of equipment and approx. area covered in M^2) ____________________
- [ ] No

10. Access for construction and installation of the roof

Materials and equipment will have to be taken up to the roof during construction and installation. The presence of scaffolding for other external works may provide a good means of moving materials to the roof.

What is the access like for construction and installation?

- ☐ Access is very good (i.e. lift directly to roof level)
- ☐ Access is OK (wide stairs to roof say one floor below roof)
- ☐ Access is poor (narrow / winding stair access only).

11. Levels of maintenance.

What is the access like for maintenance to the plants? To the roof?

- ☐ Access is very good (i.e. lift directly to roof level)
- ☐ Access is OK (wide stairs to roof say one floor below roof)
- ☐ Access is poor (narrow / winding stair access only).

12. Costs

How much is the owner prepared to pay for a green roof?

- ☐ High
- ☐ Medium
- ☐ Low

Can the costs be partially offset by the improvement in thermal performance and energy savings?

Other notes

In this section please note down any other factors which affect the installation of a retrofit green roof.

Final evaluation

Based on the review of the factors above the roof, what is the potential for green roof retrofit?

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